The spatial distribution of upstream ion events from the Earth's bow shock measured by ACE, Wind, and STEREO

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[1] Using simultaneous measurements of >40 keV upstream ions observed at ACE, Wind, and STEREO-A during the solar minimum period of 2007, day 1 through 2007, day 181, we investigate their spatial distributions by calculating their occurrence probabilities as a function of lateral and radial separation between L1 and STEREO-A. Our main results are given as follows: (1) STEREO-A observed upstream events even when it was separated from Earth by ~1750 R_E and ~3800 R_E in the radial and lateral directions, respectively. (2) The occurrence probability (~20–30%) for measuring simultaneous upstream events at L1 and STEREO-A was far greater than that expected from accidental coincidences. (3) The occurrence rate of simultaneous upstream events at L1 and STEREO-A is significantly higher inside rarefaction regions of high-speed solar wind flows (>500 km s^{-1}) that follow corotating compression regions and when there exist antisunward propagating Alfvén waves. These new results confirm the global nature of the source region and place limits on the spatial size of the interplanetary structures that could either accelerate the ions in the first place or at the very least provide them with easier access by facilitating their scatter-free transport from the Earth's foreshock into the far upstream regions traversed by STEREO-A. We suggest that the existence of large amplitude Alfvén waves with spatial scales of the order of 0.03 AU that are embedded in and get convected past the Earth by high-speed solar wind streams plays a critical and necessary role in the occurrence of upstream ion events near the Earth.

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1. Introduction

[2] Ion intensity enhancements between ~few keV and ~1–2 MeV in energy have been observed routinely upstream of the Earth's bow shock since the 1960s [e.g., *Asbridge et al.*, 1968; *Sarris et al.*, 1976; *Scholer et al.*, 1979]. Such upstream ion events are characterized by short durations (~1–2 hours), steeply falling spectra ($j \propto E^{-4}$), large (>100:1) field-aligned sunward anisotropies [*Mitchell and Roelof*, 1983; *Müller-Mellin et al.*, 2007b], and positive correlations with the solar wind speed and geomagnetic indices [e.g., *Desai et al.*, 2000]. Despite the wealth of information available, however, it is still not clear which fraction of these ions is accelerated at the bow shock [e.g., *Lee*, 1982; *Trattner et al.*, 2003] or inside the Earth's magnetosphere [*Sheldon et al.*, 2003; *Anagnaostpoulos et al.*, 2005; *Chen et al.*, 2005] and under which circumstances.

[3] An important property of these events is their simultaneous occurrence at two or more spatially distributed spacecraft. For instance, simultaneous measurements of ion events at IMP 6 & 7 spacecraft inside the magnetosphere and IMP 8 in the upstream region led *Sarris et al.* [1978, 1987] to propose that the events observed upstream of Earth probably originated from inside the magnetosphere. In contrast, using multispacecraft observations from ISEE-1 and -3, *Scholer et al.* [1981] reported that the upstream ion distributions look substantially different close to the bow shock (the so-called diffuse ions) and far upstream. In particular, they pointed out that some of the diffuse ions could leak into the upstream region and then travel mostly scatter-free because the wave activity is much lower far upstream, leading to a much more anisotropic distribution [see also *Mitchell and Roelof*, 1983]. On this basis, Scholer et al. suggested that the locally accelerated diffuse population could be the source of the highly beaming distributions seen far upstream.

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Table 1. Overview of Data Sets Used in This Survey

Spacecraft	Location	Instrument	Geometry Factor, cm^2 sr	Count Rate	Ion Energy Interval (Mainly Protons)	Look Direction	Reference
ACE	L1	ULEIS	~1	START-2	>40 keV	Fixed at 60° to spin axis; spin axis points toward Sun	*Mason et al.* [1998]
STEREO-A	<1 AU	SIT	~0.29	valid stop	>40 keV	Stabilized spacecraft; sensor view at 60° west of S/C-Sun line	*Mason et al.* [2007]
		SEPT	~0.17	3E − 1	75–137 keV	Stabilized spacecraft; sensor view at 225° west of S/C-Sun line	*Müller-Mellin et al.* [2007a]
Wind	L1	STEP	~0.4	START	>40 keV	Two telescopes fixed at 64° and 116° to spin axis; spin axis along $-Z_{GSE}$ (perpendicular to ecliptic plane)	*von Rosenvinge et al.* [1995]

[4] The suggestion of Scholer et al. was consistent with the results of *Ipavich et al.* [1981] and *Trattner et al.* [1994], who found that the fluxes of diffuse ions around ~100 keV/q near the Earth's bow shock fall off exponentially with distance, with the e-folding distances varying from ~3 R_E to 10 R_E. They interpreted these results in terms of the local diffusion length scale and connection between the spacecraft and the bow shock. More recently, *Kis et al.* [2004] using Cluster data during a single event showed that the e-folding distance of the energetic particle intensity between ~11 and 27 keV ions varied between ~0.5 and 2.8 R_E. In summary, these studies reported a significant energy-dependent increase in the e-folding distance, indicating that the more energetic particles can escape more easily into the upstream region leading to harder spectra further away from the bow shock.

[5] The launch of Geotail, Wind, and ACE in the 1990s heralded a new era of studying the simultaneous occurrence of upstream events [*Haggerty et al.*, 1999; 2000; *Dwyer et al.*, 2000]. *Haggerty et al.* [1999] and *Dwyer et al.* [2000] analyzed simultaneous observations of upstream ion events at ACE and Wind and found that the coincidence rate remained high even when the two spacecraft were separated laterally by ~70 R_E. Both studies concluded that upstream events probably originate from a source region that is large when compared with the size of the Earth's bow shock. Later, *Haggerty et al.* [2000] found that the interplanetary magnetic field orientation during a significant fraction (>40%) of upstream events observed simultaneously at four spacecraft deviated by more than ~30° from the radial direction. On the basis of this survey, *Haggerty et al.* [2000] concluded that upstream ion events probably propagate in large-scale spatial structures with radii of curvature of the order of the Earth-L1 distance ~0.01 AU that get convected past the L1 point and into the Earth's foreshock.

[6] Although these earlier results indicated that upstream ions probably originate from a large source region perhaps covering the entire size of the bow shock [see also *Scholer et al.*, 1981] and propagate in large spatial structures in the upstream region [see also *Sanderson et al.*, 1981], owing to limitations in the orbits of Geotail, Wind, and ACE, the size and nature of the spatial structures in which these ions travel in the upstream region remained undetermined. Using STEREO-A observations, more recently *Müller-Mellin et al.* [2007b] reported that the occurrence frequency of upstream events decays with increasing separation distance between the spacecraft and the Earth's bow shock with an e-folding distance of ~350 R_E. They also noted that this distance was significantly larger than that (~7 R_E) observed by *Ipavich et al.* [1981], *Trattner et al.* [1994], and *Kis et al.* [2004] for diffuse ions closer to the bow shock.

[7] In this paper we use simultaneous measurements of >40 keV upstream ions observed at ACE, Wind, and STEREO-A between 2007, day 1 and 2007, day 181 to calculate the occurrence probability of upstream events as a function of lateral and radial separation between L1 and STEREO-A. During the end of this ~6-month period, Wind (or ACE) and STEREO-A were separated up to ~1750 R_E in the radial direction and laterally in Y_{GSE} by ~3800 R_E. Despite this large separation, STEREO-A continued to observe upstream events right up until the end of our survey period. More surprisingly, we found that even at large separation distances between L1 and STEREO-A, the occurrence probability for measuring simultaneous upstream events was ≥20–30%, far greater than that expected from accidental coincidences. We discuss the implications of these results for the size of the source region, the conditions under which upstream events occur, and the size and nature of the spatial structures in which these ions populate and propagate in the upstream regions of the Earth's bow shock.

2. Instrumentation, Event Selection, and Overview

[8] We use ion measurements obtained by the Suprathermal through Energetic Particle telescope (STEP [*von Rosenvinge et al.*, 1995]) on board the *Wind* spacecraft ([*Acuña et al.*, 1995] launched in November 1994); the Ultra-Low-Energy Isotope Spectrometer (ULEIS [*Mason et al.*, 1998]) on board the Advanced Composition Explorer (ACE [*Stone et al.*, 1998], launched in August 1997), and the Suprathermal Ion Telescope (SIT [*Mason et al.*, 2007]) and Solar Electron and Proton Telescope (SEPT [*Müller-Mellin et al.*, 2007a]) on board the STEREO-A spacecraft, launched in October 2006. STEP, ULEIS, and SIT are time-of-flight *vs.* residual energy mass spectrometers that measure H-Ni ions in the ~0.02–5 MeV/nucleon energy range, while SEPT measures the residual kinetic energy of >70 keV ions. Table 1 summarizes the data sets used in this survey. We also use 10-minute and 96-second averages of the solar wind velocity and magnetic field components measured by the SWE [*Ogilvie et al.*, 1995] and MAG [*Lepping et al.*, 1995] instruments, respectively on board the Wind spacecraft.

[9] Figure 1 provides the location of the three spacecraft from day 1, 2007 to day 181, 2007 in the GSE XYZ coordinate system. During our period of study ACE and

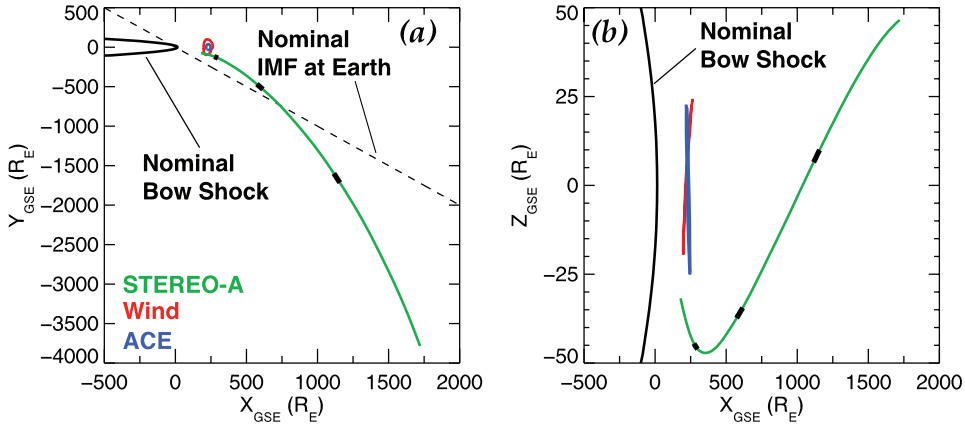

Figure 1. Trajectories of ACE (blue), Wind (red), and STEREO-A (green) from day 1, 2007 to day 181, 2007 in the GSE XYZ coordinate system. Black portions along the STEREO-A trajectory indicate three different locations where upstream events were observed simultaneously at all three spacecrafts (see also Figures 2–5).

Wind were in orbit around L1, while STEREO-A moved away from L1 and finally reached a location X$\sim$1750 R_E and Y~-3800 R_E. This vast separation between Earth, i.e., ACE and Wind, and STEREO-A has provided us with an unprecedented opportunity to investigate the spatial distribution of upstream ion events originating from the vicinity of Earth. Only STEREO-A is used in this work because during the survey period STEREO-B was in the Earth's magnetotail (not shown) and therefore was not suitably located for measuring upstream events.

[10] Above $\sim$50 keV a typical upstream ion event has steep spectra that can be characterized by a power-law index of $\sim$4 [see *Desai et al.*, 2000], implying that most of the counts are measured near the lower energy thresholds of the above instruments. For ACE/ULEIS and Wind/STEP, this corresponds to the START-2 and START count rates, respectively [see *Dwyer et al.*, 2000]. For STEREO-A/SIT and STEREO-A/SEPT, this corresponds to the Valid Stop and 3E-1 count rates, respectively. As listed in Table 1, the ACE/ULEIS/START-2, Wind/STEP/START, and STEREO-A/SIT/Valid Stop count rates are dominated by >40 keV ions. The STEREO-A/SEPT/3E-1 count rates are dominated by 75–137 keV ions. All four counting rates are dominated by protons. We remark that STEP measures heavy ions in eight sectors of two identical telescopes pointed at 64° and 116° to the spacecraft spin axis which points along the $-$Z direction in the Geocentric Solar Ecliptic (GSE) coordinate system. Thus, during a single spacecraft spin period, STEP can measure sunward and earthward flowing ions. On the other hand, the look direction of the SEPT/3E telescope lies in the ecliptic plane and measures ions traveling away from the Earth at 45° to the Sun-Earth line. Finally, the ULEIS and STEREO-A/SIT instruments fields-of-view look in the sunward hemisphere.

[11] Figure 2a provides an overview of the 10-minute averaged count rates measured at ACE, Wind, and STEREO-A from day 1, 2007 to day 181, 2007. Figure 2b shows the solar wind speed measured by Wind/SWE, while Figure 2c shows the location of the three spacecraft as a function of radial distance from Earth (also see Figures 3b and 3c). Figure 2b shows the arrival of a number of recurrent high-speed solar wind streams at Earth. Such corotating stream interaction regions dominated the structure and properties of inner heliosphere around the solar minimum conditions of 2007 [*McComas et al.*, 2006; *Mason et al.*, 2008]. At each spacecraft, we identified upstream ion events independently by requiring that the corresponding count rate increased by more than a factor of $\sim$3 over the preevent count rate which at a minimum was 3–4 counts/sec (see, e.g., Figures 4 and 5). In total, we identified 300 events at Wind/STEP, 201 events at ACE/ULEIS, and 181 events at STEREO-A/SEPT. ACE observes fewer events when compared with Wind, even though both spacecraft are near L1 probably because of the sunward orientation of ULEIS. The symbols in Figure 2c denote the occurrence times of all upstream events identified at the three spacecraft. A surprising result of our survey is that STEREO-A continued to observe upstream events right up until the end of our survey period when the lateral and radial separation from Earth was fairly large. Upstream events at such vast distances (about a factor of $\sim$20 or so greater than before) from Earth have never been reported before.

[12] Figures 3, 4, and 5 show examples of sequences of upstream events at all three spacecraft as STEREO-A moved further away from the Earth. The selected periods are shown as black bars superposed on the green curve in Figure 1 and black bars at the top of Figure 2. In order to determine the spatial distribution of upstream events, we identified events that occurred simultaneously at two spacecraft (e.g., Wind and STEREO-A) and at all three spacecraft. Since upstream events typically last $\sim$1–2 hours [see *Desai et al.*, 2000], for each event observed at Wind we also identified whether an event was observed simultaneously at STEREO-A (for two spacecraft) and at ACE and STEREO-A within a $\sim$2 hour interval centered near the peak count rate observed at Wind. Examples of events that occurred simultaneously at all three spacecraft are identified as yellow bars in Figures 4 and 5. We remark that our conservative selection criteria of requiring an increase in each count rate by at least a factor of $\sim$3 eliminates a significant number ($\sim$5–10%) of possible simultaneous events that occurred during the survey period. An example

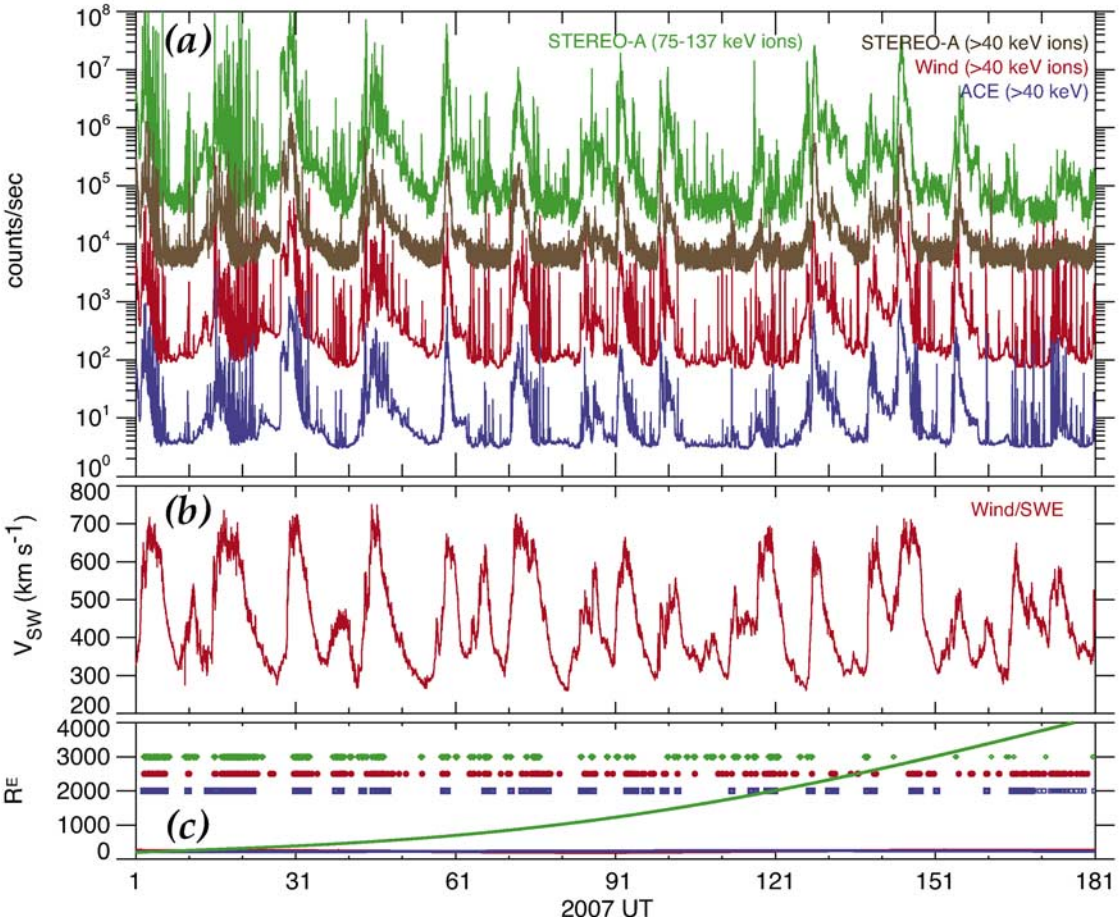

Figure 2. Overview of ACE/ULEIS, Wind/STEP, and STEREO-A/SEPT and STEREO-A/SIT measurements between day 1, 2007 and day 181, 2007. (a) Ten-minute averaged >50 keV ion count rates measured by ACE/ULEIS (blue), Wind/STEP (red), STEREO-A/SEPT (green), and STEREO-A/SIT (brown). The STEREO-A/SIT and STEREO-A/SEPT count rates are offset by a factor of 10^4 and the Wind count rate is offset by a factor of 20. (b) Ten-minute averaged solar wind speed measured by Wind/SWE. (c) Solid lines: Radial distance of ACE (blue), Wind (red), and STEREO-A (green) from Earth. Upstream events identified at STEREO-A (green diamonds), Wind (red circles), and ACE (blue squares) are also shown.

of an event that did not meet our criteria is shown as a blue bar in Figure 4. Thus the statistical results in this paper provide a lower limit for the number of simultaneous upstream events during the survey period.

3. Spatial Distribution of Upstream Events

[13] Using the identification scheme described above, we found that 90 events were observed simultaneously at Wind and STEREO-A, and 53 events occurred simultaneously at all three spacecraft. In order to determine the spatial extent of upstream events near Earth we plot in Figure 6a the occurrence probability of the 90 upstream events that were observed simultaneously at Wind and STEREO-A versus the radial (X_{GSE}, blue diamonds) and lateral (Y_{GSE}, red circles) separation between the spacecraft. The occurrence probability is obtained by grouping the number of simultaneous events observed at Wind and STEREO-A into 50 R_E separation bins and then dividing by the total number of events observed at Wind in the corresponding separation bin. To complete our analysis, we also identified events that occurred simultaneously between the remaining two pairs of spacecraft, i.e., 137 events at ACE and Wind, and 68 events at ACE and STEREO-A. The results for each pair of spacecraft (not shown) are identical to those shown in Figure 6a. Figure 6b shows the same but for the 53 upstream events observed simultaneously at ACE, Wind, and STEREO-A. The separation distances are calculated for Wind and STEREO-A.

[14] A surprising result is that upstream events continue to be observed simultaneously at two and indeed all three spacecraft even when the lateral and radial separations between STEREO-A and L1 are more than 800 R_E. Moreover, the probability of observing simultaneous upstream events at two spacecraft is ~60% when the separation is less than 200 R_E and decreases somewhat monotonically with increasing separation to ~20% when the spacecraft are separated by ~800 R_E. A somewhat similar trend is observed for upstream events occurring simultaneously at three spacecraft: the occurrence probability is ~40% when

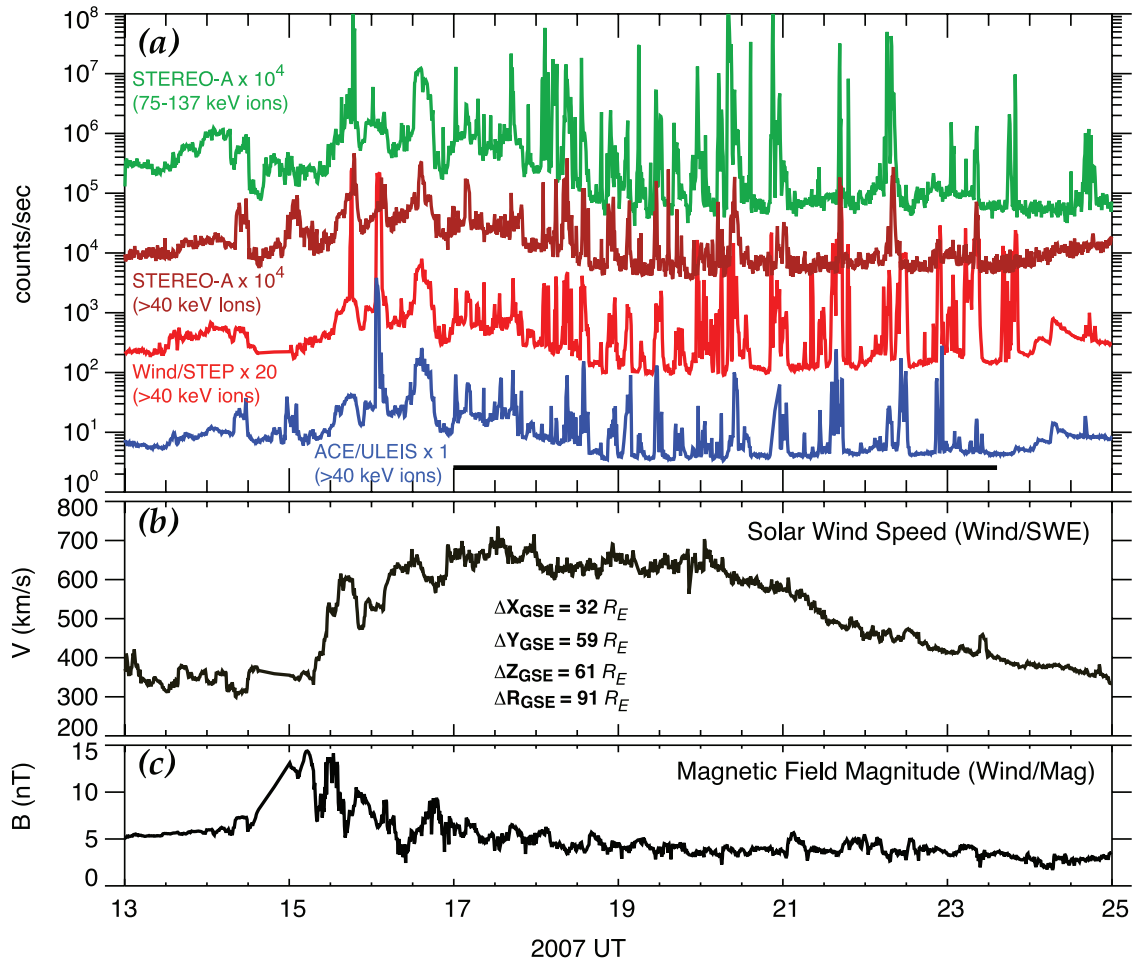

Figure 3. (a) Same as Figure 2a but from day 13 to day 25, 2007. (b) Solar wind speed measured by Wind/SWE. (c) Magnetic field magnitude measured by Wind/Mag. Also indicated are the separation distances between STEREO-A and Wind.

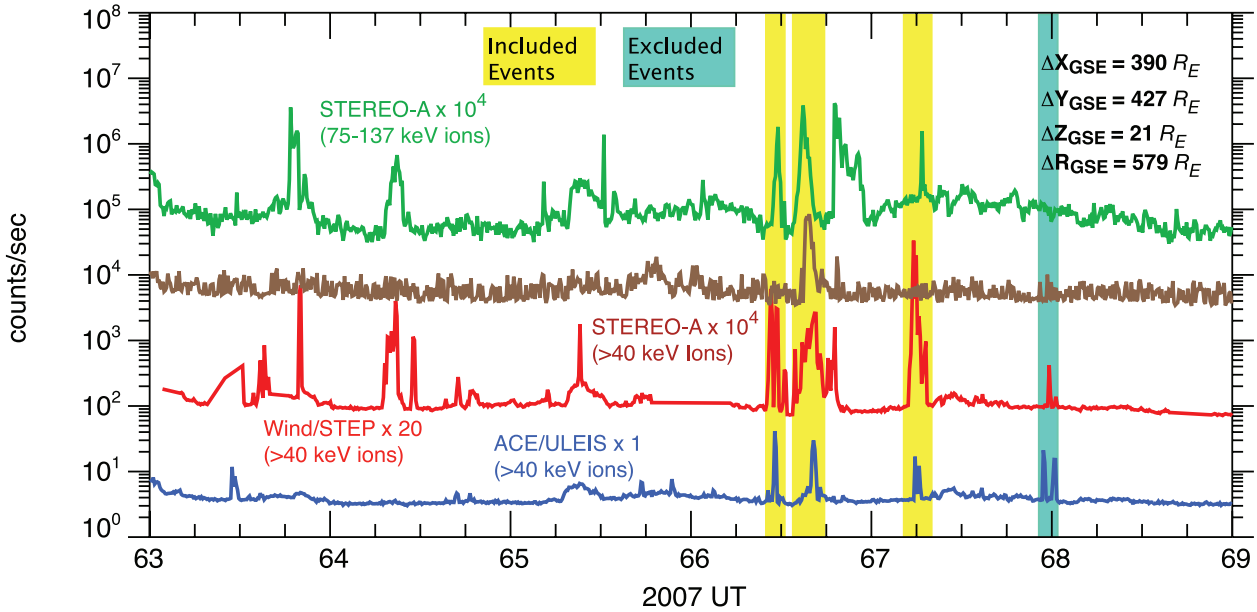

Figure 4. Same as Figure 2a but from day 63 to day 69, 2007.

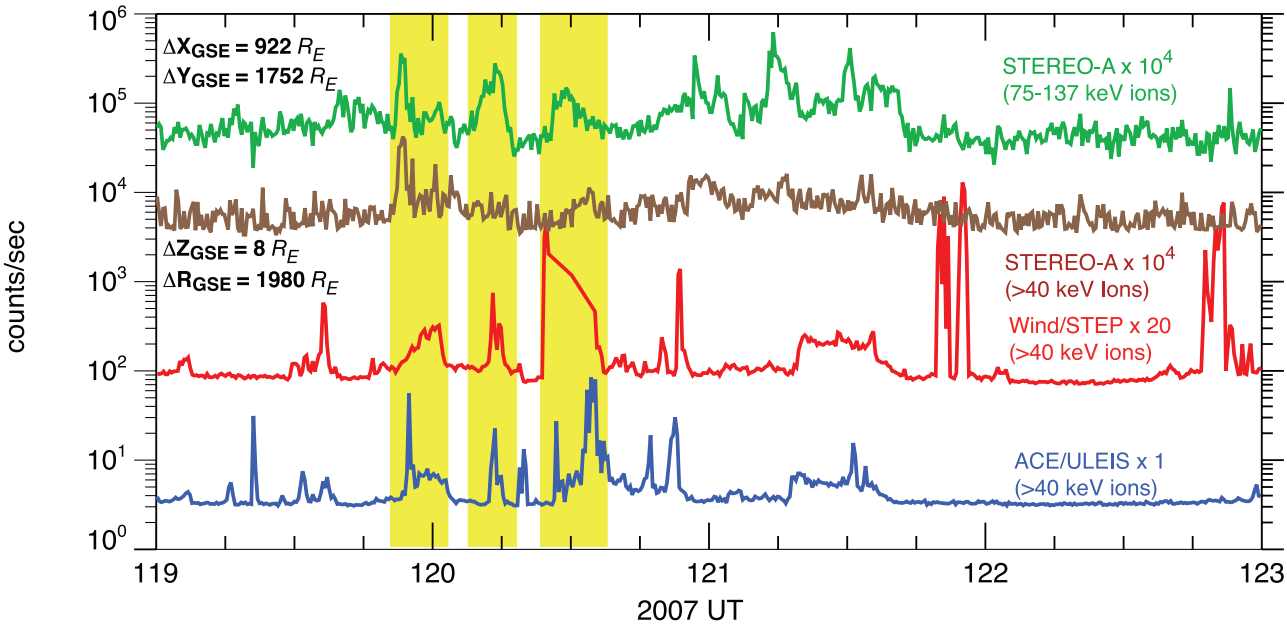

Figure 5. Same as Figure 2a but from day 119 to day 123, 2007.

the separation is less than 100 R_E but drops to 15–20% when the separation is between ~100 and 200 R_E. The occurrence probability then remains relatively constant at ~10–20% for separation distances between ~200 and 1000 R_E.

[15] In order to determine whether the simultaneous occurrence of upstream events is statistically significant or merely accidental, we estimated the accidental coincidence rate as follows [see also *Dwyer et al.*, 2000]. We shifted the STEREO-A/SEPT/3E-1 count rate by 6 days and repeated the above analysis. The "accidental coincidence rates" are shown as dashed curves in Figure 6. We also performed this analysis by shifting the SEPT count rate by 1 or more days and found similar results. The figure shows that the accidental coincidence rate of measuring upstream events simultaneously at two spacecraft is ~10%, while that of measuring upstream events simultaneously at three spacecraft is even lower at ~2–3%. This implies that the results shown in Figure 6 are likely to be statistically significant, and that the simultaneous occurrence of upstream events at ACE, Wind, and STEREO-A is not accidental.

4. Correlations With High-Speed Streams and Alfvén Waves

[16] In investigating the origin of upstream ion events near Earth, previous studies found strong positive correlations between their occurrence rates and the solar wind speed as well as with geomagnetic activity indices such as the D_{ST} and the K_P [see *Anagnostopoulos et al.*, 1998; *Desai et al.*, 2000]. In Figure 7, we investigate the occurrence rates of upstream events observed simultaneously at two and three spacecraft versus the solar wind speed V_{SW} measured at Wind. The events are grouped in bin sizes of

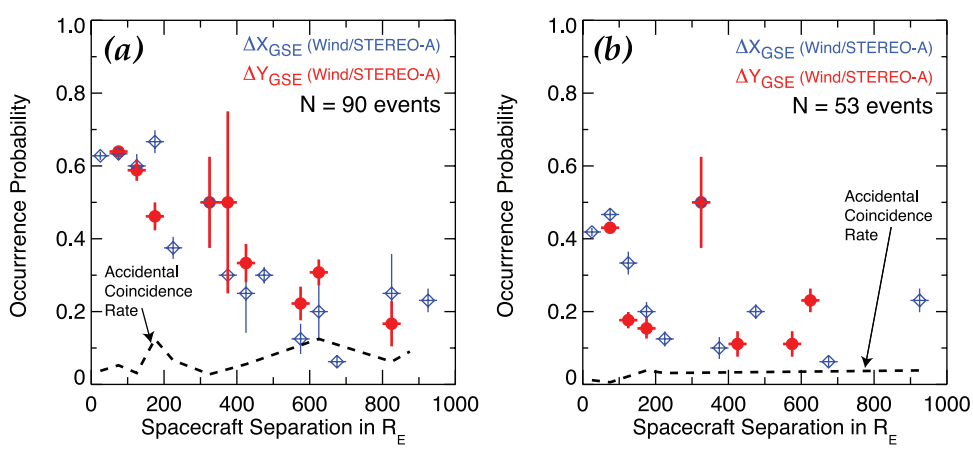

Figure 6. Occurrence probability versus spacecraft separation in X and Y as measured in the GSE coordinate system. (a) Probability of observing simultaneous upstream events at Wind and STEREO-A. (b) Same as Figure 6a but for ACE, Wind, and STEREO-A. Events are grouped in 50 R_E bin sizes.

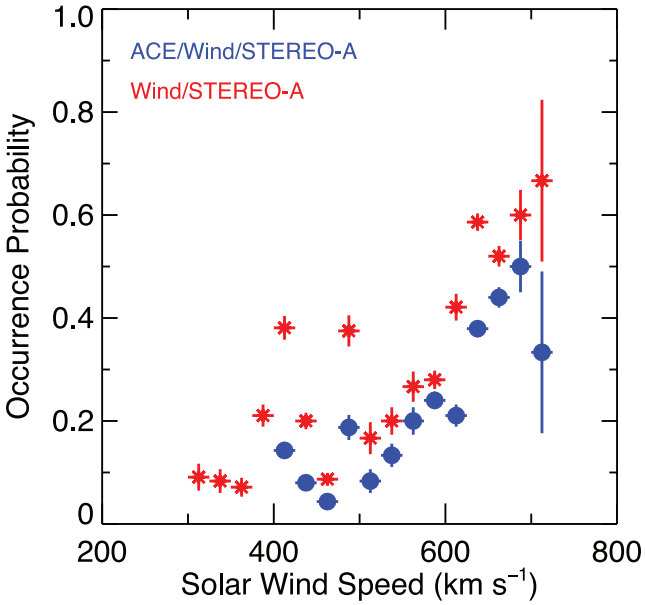

Figure 7. Occurrence probability of observing upstream events simultaneously at Wind and STEREO-A (red) and at ACE, Wind, and STEREO-A (blue) versus the measured solar wind speed at Wind. Events are grouped in 25 km s^{-1} bin sizes.

25 km s^{-1}. The occurrence probability is defined as the number of events observed simultaneously at two (or three) spacecraft divided by the number of events observed at Wind. Figure 7 clearly shows that the probability of observing simultaneous upstream events at two and three spacecraft increases dramatically when the solar wind speed exceeds 500 km s^{-1} and reaches ~70% when $V_{SW} \sim 700$ km s^{-1}.

[17] Ulysses observations during high-speed solar wind flows originating from polar coronal holes over the high-latitude southern heliosphere have revealed that such flows possess a unique property; they comprise outward propagating large amplitude Alfvén waves with spatial scales of the order of 0.01–0.1 AU [*Smith et al.*, 1995]. In order to investigate the relationship between the occurrence of upstream events at Earth and such Alfvén waves, we show in Figure 8 an example of the existence of such Alfvén waves detected at Wind during the period 2007, day 17, 2155 UT through day 23, 2231 UT. The period is shown as the solid bar in Figure 3a. The figures show correlations between fluctuations in the solar wind velocity (δV_i) and the magnetic field (δB_i) components in the Y_{GSE} and Z_{GSE} directions, where the subscript i indicates the Y or Z component. The fluctuations are computed using 10-minute averages of the solar wind velocity and the magnetic field components, e.g., $\delta V_Y = V_Y - \langle V_Y \rangle$ where V_Y is the solar wind velocity component in the Y_{GSE} direction obtained in a given 10-minute interval and $\langle V_Y \rangle$ is the solar wind velocity component along the Y_{GSE} axis averaged over a 6-hour interval. Notice the excellent correlation between δV_i and δB_i. For 781 data points a correlation coefficient $r \sim 0.7$ has a less than 0.01% chance of being exceeded by a pair of uncorrelated parameters. The average value of B_X in the GSE coordinate system for this entire period is negative, which together with the negative correlation between δV_i and δB_i essentially confirms the presence of antisunward propagating Alfvén waves [see *Belcher and Davis*, 1971].

[18] We also performed a similar analysis using 96-second averaged solar wind plasma and magnetic field data and investigated the relationship between fluctuations in the solar wind and magnetic field components during a 2-hour interval centered near the peak of each of the 300 upstream events that were identified in the Wind/STEP data. In this work we consider that Alfvén waves are present at the time of occurrence of an upstream event if the correlation coefficient between δV_i and δB_i obtained during the corresponding 2-hour interval exceeds 0.7. Although this value is rather conservative and somewhat arbitrary, we use it here to illustrate the high correspondence between the

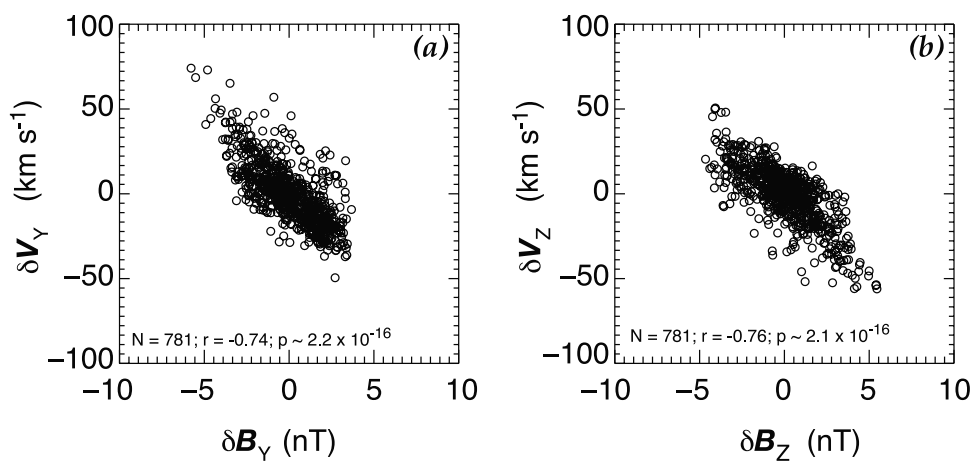

Figure 8. Scatterplots of fluctuations in the 10-min averaged solar wind velocity (δV_i) and the magnetic field (δB_i) components in the Y_{GSE} and Z_{GSE} directions about their respective mean values $\langle V_i \rangle$ and $\langle B_i \rangle$ obtained within a 6-h interval (see text for detailed definitions of δV_i and δB_i). The data are obtained from 2007, day 17, 2155 UT to day 23, 2230 UT. N, r, and p denote the number of data points, the linear correlation coefficient, and its statistical significance.

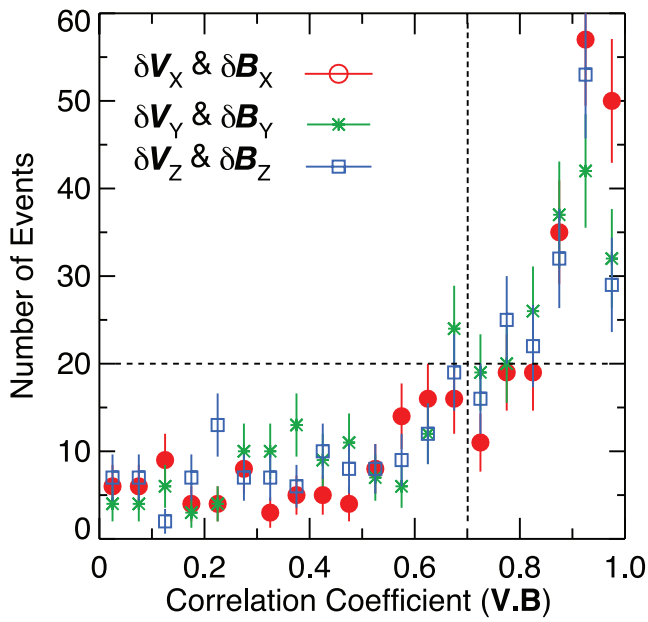

Figure 9. Histogram of 300 upstream events versus the correlation coefficient between the solar wind velocity (δV_i) and the magnetic field (δB_i) components observed within a 2-h interval centered at the peak of the events (see text for details).

presence of Alfvén waves at 1 AU and the occurrence of upstream events. Since each 2-hour interval contains 75 data points, we remark that a correlation coefficient of 0.7 or more has less than 0.01% chance of being exceeded by a pair of random uncorrelated parameters.

[19] We grouped the 300 events according to the absolute values of the correlation coefficients for the three components in bin sizes of 0.05. The histograms resulting from this analysis are shown in Figure 9. We note that the number of events increases dramatically when the correlation coefficients for all three components increases above 0.7. In summary, we find that 197 of the 300 events (~66%) occurred when the correlation coefficients were greater than 0.7. We also calculated the correlation coefficients for the 70 days when there were no upstream events at Wind. We found that only 3 of these (days 5, 10, 36) had correlation coefficients between fluctuations in the solar wind velocity and magnetic field components above 0.7. For all 300 events, we compared the sign of the correlation coefficients in conjunction with the corresponding value of B_X, and found that 275 of the 300 events were accompanied by the presence of antisunward propagating Alfvén waves. The absolute values of the correlation coefficients between δV_i and δB_i for the remaining 25 events are less than 0.2 and hence are of lower statistical significance. These results clearly indicate that the remarkable coincidence between upstream events and the arrival of high-speed streams that comprise Alfvén Waves is highly significant and unlikely to be due to random coincidences.

5. Discussion

[20] Our survey of the occurrence probability of upstream events observed simultaneously at ACE, Wind and STEREO-A between day 1, 2007 and day 181, 2007 shows the following.

[21] Upstream ion events above >40 keV in energy are observed at STEREO-A even when the spacecraft was separated from Earth radially (ΔX_{GSE}) by ~1750 R_E and laterally (ΔY_{GSE}) by ~3800 R_E.

[22] The probability of observing simultaneous upstream events at Wind and STEREO-A is ~60% when the two spacecraft are separated by ~200 R_E and decreases to ~20% when the separation increases by more than 800 R_E.

[23] The occurrence probability of observing simultaneous upstream events at all three spacecraft is ~40% when STEREO-A is separated from L1 by 100 R_E or less but drops to 15–20% when the separation is between ~100 and 200 R_E. The occurrence probability then remains relatively constant at ~10–20% for separation distances between ~200 and 1000 R_E.

[24] The occurrence probability of observing simultaneous upstream events at two and three spacecraft increases dramatically when the solar wind speed exceeds 500 km s^{-1} and reaches ~70% when V_{SW} ~ 700 km s^{-1}.

[25] Most upstream events (>66%) are accompanied by strong correlations between fluctuations in the solar wind velocity and the magnetic field components, i.e., by antisunward propagating Alfvén waves. Conversely, a lack of Alfvénic wave activity tends to coincide with days when upstream event activity was relatively low or negligible.

5.1. Size of the Source Region and Upstream Spatial Structures

[26] Previously, *Dwyer et al.* [2000] reported that there was a greater than 50% chance of observing upstream events simultaneously at two spacecraft for lateral separations up to ~70 R_E. They examined several mechanisms that could explain their observations. One possibility was that a small source filled small flux tubes that caused accidental coincidences between the spacecraft; this was ruled out since the observed rate of coincidence was much higher than calculated assuming accidentals. Another possibility was a small source that filled a small magnetic flux tube that rapidly moved between the spacecraft; this was ruled out since some events lasted more than an hour. Another possibility was that cross field diffusion far upstream from the bow shock let the particles spread out causing the coincidences; this was ruled out since the particle events showed evidence of being confined to the flux tubes, namely, abrupt onsets (see Figures 3–5) and strong anisotropies [see *Desai et al.*, 2000].

[27] In summary, the results of *Dwyer et al.* [2000] along with the studies of *Haggerty et al.* [1999, 2000] indicate that upstream events occur when a spacecraft enters and leaves magnetic structures or sheets [see, e.g., *Sanderson et al.*, 1981] that are filled with upstream ions. The results shown in this paper are hence consistent with the main conclusions of the earlier studies and support the notion that the source region is probably at least as large as the bow shock [see also *Scholer et al.*, 1981] and further that the ions propagate within large-scale spatial structures that populate the upstream region. As pointed out by *Dwyer et al.* [2000] the large source volume might be due either to a large source or acceleration region filling substantial portions of the upstream region or a small source region

followed by enhanced perpendicular transport across field lines in the upstream regions closer to the bow shock where self-generated wave activity is more intense [e.g., *Lee*, 1982].

[28] The fact the occurrence probability of observing simultaneous upstream events remains relatively high (~10–20%) for separation distances up to ~1000 R_E could partly be a result of the relative location of STEREO-A, which moved nearly along the nominal Parker spiral direction (see Figure 1) during the survey period. In a future study we will examine the orientation of the local magnetic field and the magnetic connectivity between each of the three spacecraft and the Earth's bow shock during such simultaneous events observed over large distances.

[29] A key question that the new observations from STEREO-A have enabled us to address is the nature and size of the volume or the spatial structures that enable vastly separated spacecraft to observe upstream events simultaneously. The results of Dwyer et al. indicated that this structure may be roughly cylindrical, while *Haggerty et al.* [2000] concluded that upstream events propagate in large-scale spatial structures with radii of curvature of the order of the Earth-L1 distance that are convected past L1 and into the Earth's foreshock region. Our results indicate that upstream events are observed simultaneously at a rate of ~20% even when the spacecraft are separated radially or laterally by ~800 R_E, thereby implying that the size of the spatial structures in which these events propagate is at least as large as ~800 R_E (~0.04 AU) in both the radial and lateral directions near the ecliptic plane. We believe that these structures are likely to be even larger because STEREO-A continued to observe upstream events even when it was separated from Earth by more than ~3800 R_E laterally and ~1600 R_E in the radial direction. This implies that upstream events propagate inside interplanetary structures with spatial scales at least of the order of ~0.06 × 0.16 AU in the radial and azimuthal directions, respectively.

[30] We remark that the spatial size of the interplanetary structures that we have deduced from these observations are consistent with previous measurements of the solar wind and the interplanetary magnetic field structures near Earth. For instance, *Matthaeus et al.* [1986] studied the characteristic time of correlations between the interplanetary magnetic field and the solar wind speed measured at two different times from a single spacecraft and found the average correlation scale length to be ~4.9 × 10^6 km (~0.03 AU). Likewise, *Mazur et al.* [2000] and *Giacalone et al.* [2000] inferred that the average width of flux tubes in which particles accelerated in impulsive solar flare events propagate to Earth was on the order of ~4.7 × 10^6 km (~0.03 AU). More recently, *Neugebauer et al.* [2006] showed that the particle profile patterns in association with interplanetary shocks near Earth also exhibit a correlation scale length of ~2.97 × 10^6 km [~0.02 AU].

5.2. Relationship Between Upstream Spatial Structures and the Acceleration and Transport of Upstream Ions

[31] From Figures 2, 3, and 7 we also note that the occurrence of upstream events tends to coincide with the arrival of corotating high-speed streams at Earth. Such high-speed streams dominate the large-scale structure and properties of the inner heliosphere inside ~5 AU during solar minimum conditions. Their arrival at Earth also tends to energize the Earth's magnetosphere which, in turn, results in increasing geomagnetic activity [see *Baker et al.*, 1994]. Thus our results shown in Figure 7 are qualitatively consistent with previously reported positive correlations between the occurrence probability of upstream events and the solar wind speed and the K_P index [see *Anagnostopoulos et al.*, 1998; *Desai et al.*, 2000].

[32] In particular, our results are consistent with those of *Trattner et al.* [1994]. They showed that the solar wind speed (the component parallel to B) correlates strongly with the spectral slope of upstream events in the energy range between ~80 and 160 keV/q, close to the bow shock. Trattner et al. showed that the e-folding energy of the observed diffuse (and isotropic in the solar wind) population, which typically is an exponential in E/q, varied from about 10 keV for 200 km/s to 25 keV for 700 km/s. This could lead to substantial changes in the observed intensity of upstream events at ~40 keV and above, i.e., the energy range for this survey, and thereby result in the occurrence of more intense events during faster solar wind flows.

[33] We note that corotating compression regions near Earth orbit generally arrive ~1–2 days prior to the arrival of the associated high-speed streams [e.g., *Richardson*, 2004]. The upstream ion events are observed almost immediately after the compression regions are convected past Earth, i.e., when the spacecraft is completely immersed in the rarefaction regions and the high-speed solar wind streams. An example of the relative timing of the arrival of solar wind compression and rarefaction regions, and upstream events can be seen in Figure 3 [see also *Mason et al.*, 1996]. Ulysses observations have revealed that such high-speed solar flows comprise outward propagating large amplitude Alfvén waves with spatial scales of the order of ~0.01–0.1 AU [*Smith et al.*, 1995]. Indeed, our results demonstrate that the majority (>66%) of upstream events are accompanied by strong correlations between fluctuations in the solar wind velocity and the magnetic field components, i.e., by Alfvén waves. Furthermore, we find that a lack of Alfvénic wave activity tends to coincide with periods when upstream event activity was negligible.

[34] On the basis of these new observations, we suggest that regardless of the processes by which the upstream ions are accelerated, their production and occurrence probably depends on some combination of the arrival of compression regions at Earth followed by Alfvén waves with scale sizes of the order of 0.01 AU or more that are embedded within the rarefaction regions of the high-speed streams. This is illustrated in the cartoon shown in Figure 10. We suggest that the existence of such Alfvén waves play a critical and necessary role in the occurrence of upstream ion events near the Earth as well as for their subsequent transport to and observability (1) at large distances, or (2) in sunward looking sensors such as ACE/ULEIS, or (3) during periods of nonradial IMF [e.g., *Haggerty et al.*, 2000].

[35] We recognize that there are at least three possibilities that could account for the acceleration and transport of upstream ion events near Earth, namely, (1) the compression region first energizes solar wind and magnetospheric ions inside the Earth's magnetosphere; the subsequent arrival of the rarefaction region enables the magnetosphere to expand and release these accelerated ions from multiple locations

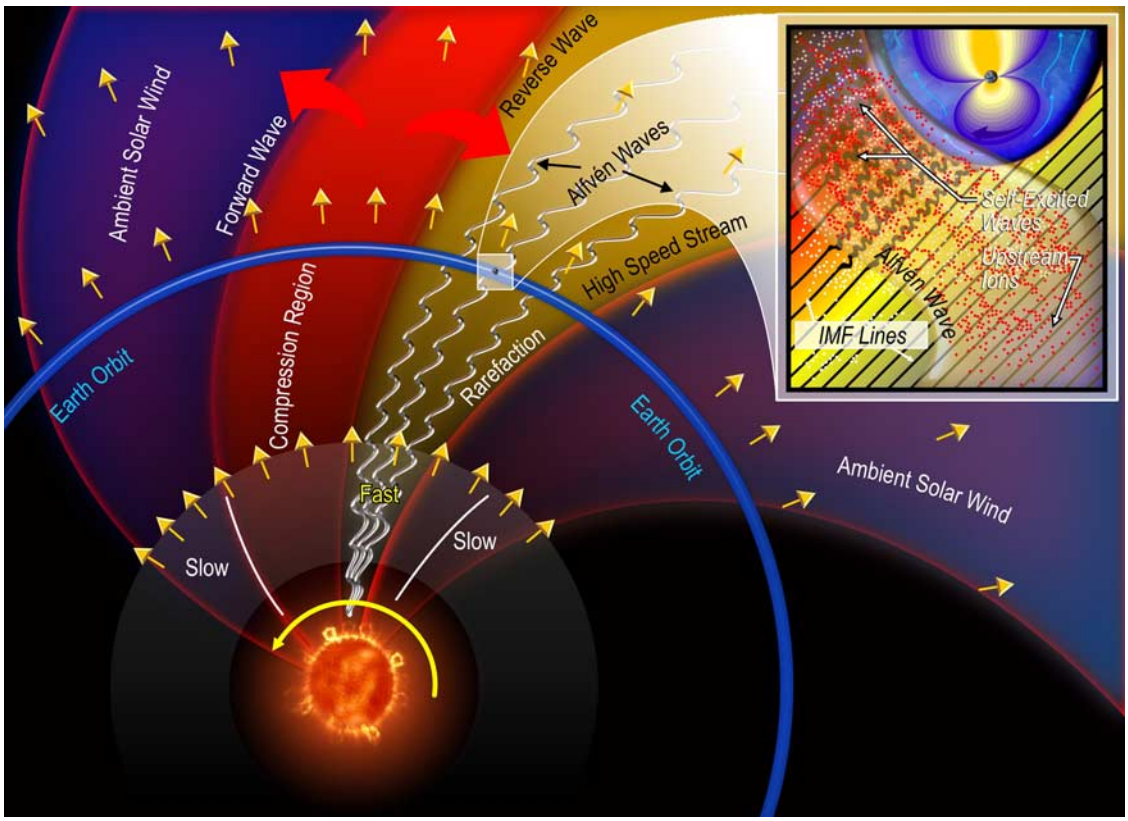

Figure 10. Cartoon showing conditions that are critical for observing upstream ions simultaneously at vastly separated spacecraft, ACE, Wind, and STEREO-A, during solar minimum conditions of the first 6 months of 2007. Our results indicate that the acceleration and propagation of >40 keV ions in the upstream regions depend on the arrival of large amplitude antisunward propagating Alfvén waves with scale sizes of the order of 0.01 AU or more that are embedded within the rarefaction regions of the high-speed streams that follow corotating compression regions. The Alfvén waves facilitate scatter-free transport of upstream ions far away from the Earth's bow shock.

on the Earth's bow shock [e.g., *Anagnostopoulos et al.*, 2005] and the presence of large amplitude Alfvén waves provides access to the upstream region and a channel for scatter-free propagation, (2) the compression region heats and accelerates solar wind ions inside the magnetosheath and at the bow shock [*Lee*, 1982], the arrival of high-speed streams with the embedded Alfvén waves "punctures" the magnetosheath/bow shock and releases the accelerated ions from several locations simultaneously, the Alfvén waves then act as conduits or spatial structures in which the ions can propagate scatter-free, and (3) solar wind ions are accelerated by multiple scatterings between the large amplitude Alfvén waves themselves and the Earth's bow shock which expands outward into the high-speed wind; in this case the compression region itself plays a relatively minor role in accelerating the upstream ions, while the Alfvén waves play a key role not only in accelerating the ions but also acting as spatial structures in which the ions propagate freely.

[36] Scenario (1) represents some form of global magnetospheric leakage, while the latter two scenarios represent first-order Fermi acceleration near the bow shock followed by scatter-free transport. Although at this stage we cannot rule out any of these scenarios, we point out that each requires the presence of large amplitude Alfvén waves to act as large-scale spatial structures that provide the accelerated ions scatter-free access to the upstream interplanetary medium (see Figure 10).

[37] We also note that scenario (3) is remarkably similar to the first-order Fermi acceleration model of *Freeman and Parks* [2000]. These authors presented detailed model calculations of energy spectra of upstream solar wind heavy ions that are scattered and accelerated between large rotations in the interplanetary magnetic field and the Earth's bow shock. The results presented here clearly show that such rotations are likely to be Alfvén waves with spatial scales of the order of 0.01 AU or more. Indeed, we also found strong correlations between fluctuations in the magnetic field and solar wind velocity components during 1994, days 324–330 (not shown), i.e., the period shown in Figure 1 of the Freeman and Parks paper when the Wind spacecraft observed a series of upstream events that extended up to ~2 MeV in energy.

[38] Combining scenario (3) where the Alfvén waves play a key role in accelerating the ions with the *Freeman and Parks* [2000] model, we speculate as follows. The situation is illustrated in Figure 10. First, the corotating compression region compresses and energizes the magnetosphere. After the compression region passes the Earth, the magnetosphere and the bow shock expand outward toward the Sun within the rarefaction region and into the high-speed solar wind

stream. The Earth's bow shock and the large amplitude Alfvén waves embedded in the high-speed streams act as converging magnetic mirrors which scatter and accelerate the ions via shock drift or first-order Fermi acceleration processes as modeled by *Freeman and Parks* [2000]. The accelerated ions then propagate freely in these large-scale Alfvénic structures and get observed simultaneously at ACE, Wind, and STEREO-A. We remark that a thorough characterization of these Alfvén waves and their exact relationship with upstream ion events clearly requires further statistical analysis, followed by detailed case studies and modeling, which are beyond the scope of this paper.

[39] Finally, we note that *Freeman and Parks* [2000] predicted that this process was likely to accelerate solar wind O^{6+} ions to higher energies than protons. These model calculations are indeed qualitatively consistent with the results of *Mason et al.* [1996] and *Desai et al.* [2000] which showed that the high energy portion (above ~500 keV in total energy) of the energy spectra in upstream events was dominated by heavier solar wind-like ions such as CNO, NeS, and Fe. However, we note that ion composition measurements obtained over the last decade or so have indicated that magnetospheric leakage and first-order Fermi acceleration at the Earth's bow shock may not be mutually exclusive [*Möbius et al.*, 1986; *Christon et al.*, 2000; *Posner et al.*, 2002; *Keika et al.*, 2004]. For instance, the fact that the heavy ion composition in the majority of upstream events above ~100 keV depends on the phase of the solar cycle and is essentially dominated by solar wind, CIR, or SEP-like material [*Desai et al.*, 2000, 2006] appears to favor acceleration of suprathermal ions of solar or interplanetary origin at the bow shock as a dominant mechanism. In contrast, the simultaneous but less frequent presence of ionospheric species like N^+ and O^+ ions [see, e.g., *Möbius et al.*, 1986; *Christon et al.*, 2000; *Posner et al.*, 2002] also indicates that Fermi acceleration near the bow shock must occasionally be accompanied by leakage from inside the magnetosphere. Thus the main challenges for any model of upstream ion production is to quantitatively account for the vast variety of observations associated with these events [see *Desai et al.*, 2000, 2006] while taking account of the new observations reported in this paper.

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