On the origin of the energetic ion events measured upstream of the Earth's bow shock by STEREO, Cluster, and Geotail

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[1] In 2007 during the declining phase of the solar cycle the energetic upstream ion events occurred mainly after a corotating interaction region passed the Earth's magnetosphere. We study the relation between these upstream events observed from about 70 to 1750 R_E away from the Earth and observations in the vicinity of the terrestrial bow shock (up to 30 R_E). For this purpose, simultaneous measurements of energetic ions from STEREO A and STEREO B (far upstream region) and from Cluster and Geotail (near the bow shock) are used. In all cases the energetic ions far upstream are associated with the upstream ion events near the bow shock. The upstream events are observed simultaneously mainly when the magnetic field is pointing along the line joining those satellites in the far upstream region with those near the terrestrial bow shock. The upstream events near the bow shock often coincide with sunward directed electron bursts, increased *AE* index (>200 nT), nonexponential proton spectra, and most important the presence of O^+ ions, all of which imply at least partly a magnetospheric origin. In ~57% of cases the upstream ion events near the bow shock are associated with electron bursts and/or with the presence of O^+, and ~40% of the latter events are associated with electron bursts at STEREO A. Although we present strong evidence that the events are partially of magnetospheric origin, we do not exclude the presence of the ions accelerated at the bow shock.

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1. Introduction

[2] The origin of the energetic ions observed upstream of the Earth's bow shock has been investigated for the last four decades and essentially two processes have been identified: bow shock acceleration of solar ions and leakage from the magnetosphere.

[3] Particles of solar wind origin can be accelerated at the terrestrial bow shock by various acceleration mechanisms. These could be reflected ion beams seen at the quasi-perpendicular bow shock and so-called diffuse particles associated with the quasi-parallel bow shock [*Bale et al.*, 2005; *Eastwood et al.*, 2005]. At the quasi-perpendicular bow shock energetic ions of solar wind origin can be accelerated by shock drift acceleration, and then travel upstream to the large distances [*Anagnostopoulos and Kaliabetsos*, 1994; *Anagnostopoulos et al.*, 2009]. Early multispacecraft studies by *Scholer et al.* [1980a] presented simultaneous observations of energetic particles using data from ISEE-1 and ISEE-3 which were separated by about 200 R_E in the GSE X direction. They observed an isotropic distribution of particles close to the bow shock and the particles moving essentially scatter-free in the sunward direction at large distances. These observations were interpreted as multiple acceleration between upstream scattering centers and the bow shock or downstream and upstream scattering centers. Upstream events observed close to the bow shock often show an exponential decay in the particle density with increasing distance from the Earth's bow shock [*Ipavich et al.*, 1981; *Trattner et al.*, 1994; *Kronberg et al.*, 2009], in agreement

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with the Fermi acceleration mechanism. The solar wind ions can also be accelerated via reflection between the bow shock and short large-amplitude magnetic structures (SLAMS) in the parallel and quasi-parallel regime [*Burgess et al.*, 2005; *Kucharek et al.*, 2008].

[4] Another possible source of energetic particles observed upstream of the Earth's bow shock is the magnetosphere. To this conclusion came observational studies, either with one spacecraft in the magnetosphere and the second in the upstream region [e.g., *Sarris et al.*, 1978; *Pavlos et al.*, 1985; *Anagnostopoulos et al.*, 1986; *Sarris et al.*, 1987] or with observations from only one spacecraft [e.g., *Sarris et al.*, 1976; *Christon et al.*, 2000; *Sarafopoulos et al.*, 2000, 2001; *Anagnostopoulos et al.*, 2005]. Observations by *Keika et al.* [2004] suggest that ions accelerated in the magnetosphere leak out, in particular when geomagnetic activity is high, where they then mix with solar wind ions accelerated at the bow shock. Several mechanisms can be responsible for the escape of ions from the magnetosphere, as for example the continuous drift of energetic particles to the magnetopause and their subsequent escape across a tangential discontinuity magnetopause [*Paschalidis et al.*, 1994]; or the bursty ion escape resulting from magnetic reconnection [*Kasahara et al.*, 2008]. The escape routes of energetic particles from the magnetosphere are as follows: escape of high-energy ring current/dayside plasma sheet particles through the magnetopause, escape through antisunward flow in the nightside plasma sheet and escape of terrestrial ion beams through the lobe [*Seki et al.*, 2001]. After escape from the magnetosphere the particles drift and get observed at large distances from the Earth [e.g., *Gómez-Herrero et al.*, 2009]. *Posner et al.* [2002], using data from Wind, concluded that suprathermal heavy ion events observed between the Earth's bow shock and L1 point are occurring when a high-speed stream associated with nonlinear Alfvén waves, which produce the rapidly fluctuating southward interplanetary magnetic field (IMF) component, encounters the Earth's magnetosphere and triggers substorms. Substorms are significant sources of the heavy ions that could leak from the dayside magnetopause. Furthermore, a large number of energetic ions are lost into the magnetosheath during magnetic storms, particularly during the main and early recovery phases.

[5] Ions can also be accelerated in the solar wind by forward and reverse shocks associated with the corotating interaction regions [e.g., *Barnes and Simpson*, 1976; *Fisk and Lee*, 1980]. The alternative acceleration mechanisms in corotating interaction regions (CIRs) have been discussed in a review work by *Richardson* [2004].

[6] Indeed, energetic ion upstream events often occur in association with rarefaction regions of high-speed solar wind flows that follow corotating compression regions. Thus *Mason et al.* [1996] suggest that the CIRs provide the seed population for energetic ion events, that are then further accelerated at the Earth's bow shock. However, *Anagnostopoulos* [1998] proposed that a source of the same set of upstream events is a magnetospheric leakage. Recently, *Desai et al.* [2008] published results from simultaneous multispacecraft observations (ACE, STEREO A and Wind) of energetic upstream ion events at distances up to 4200 R_E. Most of these events were associated with high-speed solar wind streams and with antisunward propagating Alfvén waves. Large-amplitude Alfvén waves which provide access to the upstream region and a channel for scatter-free propagation are essential in this context.

[7] Therefore, there are still controversial theories on the question: Where do the upstream energetic particle events come from, especially up to large distances? In order to answer the question, we examine whether the events observed far upstream are accompanied by the events in the vicinity of the bow shock and (if they are accompanied) where they are accelerated: at the Earth's bow shock or/and in the magnetosphere? We use simultaneous observations located far upstream (STEREO A and B) and near the Earth's bow shock (Cluster and Geotail). The multispacecraft observations may provide new insights into the question.

2. Instrumentation

[8] In this study we used the ion and electron measurements in the far upstream region obtained on board the nonspinning STEREO A and STEREO B spacecraft by the Solar Electron and Proton Telescopes (SEPT) [*Müller-Mellin et al.*, 2007] which cover the energy range between 75 keV and 6.5 MeV for protons and between 65 keV and 400 keV for electrons. These telescopes have four sensors which look: sunward, antisunward, northward and southward with view cone 52° and accumulation time 60 s. The central line of the sun- and antisunward sensors is 45° from the SC-Sun line.

[9] We use proton data from the near bow shock region measured by the Cluster 4 spacecraft [*Escoubet et al.*, 2001], the Research with Adaptive Particle Imaging Detectors (RAPID) instrument [*Wilken et al.*, 2001], Imaging Ion Mass Spectrometer (IIMS) which provides 3-D proton distributions in the energy range from 30 keV to 1.5 MeV, every ~2 min, from 3 ion heads, each with an acceptance angle of 60° in the polar plane. Unfortunately the central head of this spectrometer is damaged leading to a gap in the measured ion distribution. Therefore the instrument measures ions arriving from northward and southward directions. In this study we use omnidirectional fluxes. The electron measurements on the RAPID instrument were taken by the Imaging Electron Spectrometer (IES) in the energy range from 37 to 407 keV and we used in this work data with 1 min time resolution. The ion pitch angle distributions at energies from 1 to 40 keV were obtained by the Cluster Ion Spectrometry (CIS), Hot Ion Analyzer (HIA) [*Rème et al.*, 2001].

[10] We also use proton data from the near bow shock region obtained from the Geotail spacecraft (spin axis nearly perpendicular to the ecliptic) by the Energetic Particles and Ion Composition (EPIC) [*Williams et al.*, 1994] instrument with two identical Ion Composition Subsystem sensors (ICS), oriented above and below the ecliptic plane for complete angular coverage with acceptance angle 30° and time resolution 48 s in the energy range from 46 keV to 814 keV. The electron data were obtained from the same sensor with a time resolution of 3 s in energies above 38 keV. For the determination of the heavy ion composition we use another EPIC sensor, the Suprathermal Ion Composition Spectrometer (STICS) which measures ion mass and determines the charge state. It provides angular coverage of ~4π sr in the energy range from 9 to 210 keV/e with time resolution of 24 s.

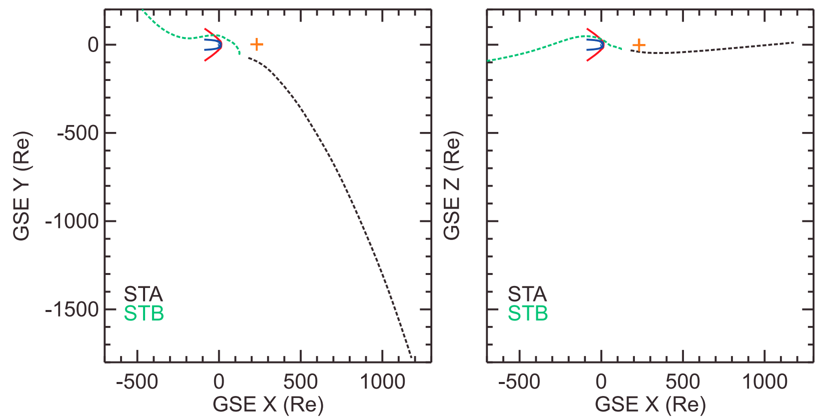

Figure 1. Projections of STEREO A and STEREO B trajectories and the bow shock (red) onto the (left) X-Y and (right) X-Z planes in GSE, for the time period between 1 January and 5 May 2007. The L1 point is denoted by the orange cross.

[11] The magnetic field measurements were obtained by STEREO/IMPACT Magnetic Field Experiment [*Acuña et al.*, 2008]; by the fluxgate magnetometer (FGM) [*Balogh et al.*, 2001] onboard Cluster; and by Magnetic Fields Measurement (MGF) on Geotail [*Kokubun et al.*, 1994].

3. Observations

[12] The purpose of the present paper is to investigate the origin of the upstream events observed by STEREO A/SEPT at distances up to ~1750 R_E from the Earth, reported by *Desai et al.* [2008]. In our study we consider events from 2 January to 5 May 2007.

[13] In Figure 1 the related trajectories of STEREO A, STEREO B in the GSE coordinate system are shown. STEREO A was moving away from the Earth to X ~ 1190 R_E and Y ~ 1800 R_E during the period of our study. STEREO B moves in opposite direction from the L1. Cluster and Geotail were orbiting the Earth so that every several days they encounter the region upstream of the Earth's bow shock. The polar trajectories of the Cluster spacecraft reach radial distances of up to ~20 R_E from the Earth. Geotail, with its in-ecliptic orbit, during this time was mainly in the morning sector, upstream of the Earth's bow shock, and reached a maximum distance of ~30 R_E.

[14] The proton intensity time profile for the energies from 101 to 220 keV measured by STEREO A is presented in Figure 2. Following the CIR flux increases, which last several days (~week) we note many spikes of the intensity time profile. These spikes are the so-called upstream events. They are characterized by short durations (~1–2 hours) and steeply falling spectra (a power law index of the particle intensity versus energy is ~4, for comparison in CIRs a power law index is ~2–3). *Desai et al.* [2008] selected events using the following criteria: the count rate increases by more than a factor of ~3 over the pre event count rate and there are at least 3–4 counts/s (0.01–0.04 [cm^2 s sr keV]$^{-1}$). The events are also characterized by sunward particle flow. For the time period from 2 January to 5 May 2007 *Desai et al.* [2008] found 166 events which satisfy the criteria above.

[15] Our next step is to find out if during far upstream observations of energetic events by STEREO A we could see simultaneous events at Cluster and Geotail near the bow shock.

3.1. Event Example

[16] For an illustration of simultaneous observations we choose an event on 18 January 2007 as an example. For this event, observations by STEREO A and B, Cluster and Geotail were available. Figure 3 shows the spacecraft constellation for this day. STEREO A was furthest away, located at [270, −120, −15]R_E and STEREO B was located at [85,11, −12]R_E. Closer to the Earth, we have Cluster located immediately upstream of the Earth's bow shock, at [14,13, −12]R_E; Geotail located at [25, −13, −7]R_E. The

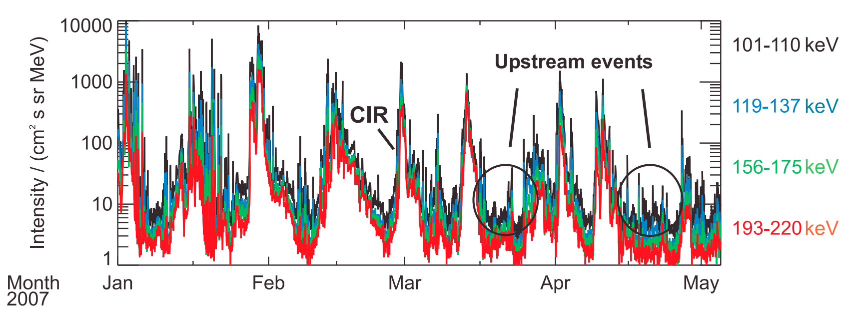

Figure 2. Figure 2 shows 1 h averaged proton intensity from the SEPT/STEREO A antisunward sensor, at energies 101–110, 119–137, 156–175, and 193–220 keV from 1 January to 5 May 2007.

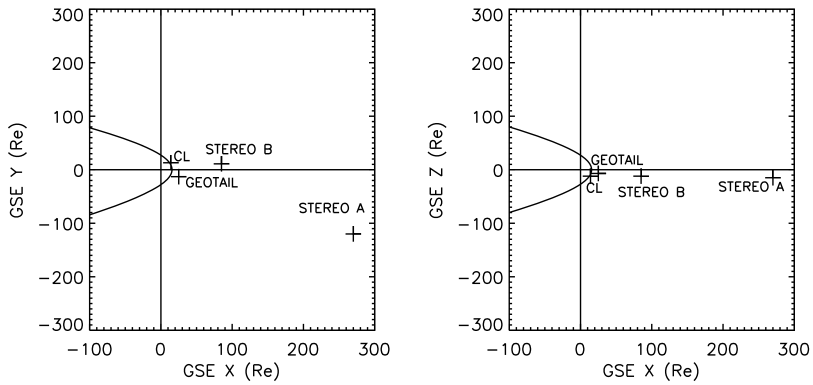

Figure 3. Projections of STEREO A and B, Cluster 4, Geotail, and bow shock locations onto the (left) X-Y and (right) X-Z planes in GSE, during the event on 18 January 2007, ~0800 UT.

magnetic field observed by STEREO A and STEREO B was directed toward the terrestrial bow shock.

[17] Figure 4 presents observations of the ion upstream events measured close to the terrestrial bow shock by Cluster from 28 to 374 keV and Geotail from 67 to 195 keV (for protons) and far upstream by STEREO A from 101 to 137 keV. The ion upstream events are denoted by transparent wide bars. Here we do not show the ion upstream events observed by STEREO B. We see that the intensities of ions observed by STEREO A flowing toward the Sun (antisunward sector) are higher than those flowing toward the Earth (sunward sensor) with an average anisotropy of about 3.

[18] The upstream event measured by Cluster/RAPID at higher energies is also observed at the lower energies (1–40 keV) measured by Cluster/CIS/HIA. This event is associated with an anisotropic, intermittent sunward ion flows at the lower energies near the bow shock, for example at 0823 UT, shown in Figure 5. In Figure 5 (top) one can see cross sections of 3-D ion distributions in the $V_{\perp 1}$ versus $V_{\|}$ velocity space, where $V_{\|}$ and $V_{\perp 1}$ are the velocity components parallel and perpendicular to the magnetic field. The plane of the cross section is defined along the magnetic field and the solar wind bulk velocity vector. The back-streaming ions are found at $\sim V_{\|} = -1000$ km s^{-1} (i.e., at energy about 5 keV) in this plot. In order to check the gyrotropy, the 3-D ion distributions in the $V_{\perp 1}$ versus $V_{\perp 2}$ velocity space are plotted, where $V_{\perp 2}$ is the velocity component perpendicular to the magnetic field for the cross section at $V_{\|} = -1000$ km s^{-1}, since the back-streaming ions are found at $\sim V_{\|} = -1000$ km s^{-1}. Therefore, from this plot we can conclude that during the upstream event ions at ~5 keV are intermittently flowing away from the bow shock nearly along the field line with some gyration.

[19] The upstream ion events shown in Figure 4 are associated with electron beams (denoted by the narrow transparent bars) which were observed by STEREO A, STEREO B at 55 to 125 keV, Geotail at energies >38 keV and Cluster at 37 to 94 keV (we do not show Cluster/RAPID observations in this case). The flow direction of the electron bursts at ~0940 and at ~1300 UT is mainly sunward at Geotail and STEREO A. The flow distribution of electrons at ~0940 is shown in Figure 6 where the electron integral intensity measured by Geotail/EPIC in many directions is presented in GSE.

[20] During ~92% of the event duration the *AE* index was larger than 200 nT implying high geomagnetic activity. At Geotail a proton power law spectrum in the energy range from 77 to 522 keV is observed during the period of the strongest ion intensity at ~0840 UT. According to *Scholer et al.* [1981] bursts of magnetospheric origin are often represented by a power law spectra in energy.

[21] Additionally, during the time period from 0740 to 1010 UT the percentage of the averaged omnidirectional counts/per event of O^+ (at 55.74 to 212.14 keV/e) to (O^+ and O^{6+} (at 9.38 to 35.70 keV/e)) (see description about these data below) is 80%. The count per event was >3 for both O^+ and O^{6+} in this case. This means that the low-charge-state oxygen which is of magnetospheric origin is dominating.

3.2. Statistical Characteristics of the Upstream Events Near the Bow Shock

[22] Of the 166 events from the *Desai et al.* [2008] data set, for 117 events simultaneous observations by STEREO A and Cluster and/or Geotail were possible. The upstream events were searched at the following energies: by STEREO A at 101 to 137 keV, by Cluster 4 at 28 to 374 keV and by Geotail at 67 to 195 keV. An example of such an event is shown in Figure 4. In all cases the upstream events are also observed near the bow shock within the time window of half an hour. As an upstream event we define an increase of the differential flux in at least 3 times than the pre-event level.

[23] Most of the events observed by STEREO A and Cluster are associated with anisotropic, intermittent sunward ion flows near the bow shock at energies 1–40 keV (Cluster/CIS), similar to the field-aligned flow shown by Figure 5 (top) (seen at $V_{\|} \sim -1000$ km s^{-1} from 0823:30 UT to 0823:59 UT).

[24] In approximately 56% of the cases (65 out of 117 events) the ion upstream events near the bow shock are accompanied by electron bursts at energy >38 keV. For an electron burst we require that the electron flux should be at least 2 times higher than the background and contains at least 2 measurements for one burst. The electron bursts according to *Sarris et al.* [1978], *Formisano* [1979], and *Scholer et al.* [1981] are signatures of magnetospheric origin. Also *Baker et al.* [1979] stated that long-time energetic proton enhancements occurring in the plasma sheet during

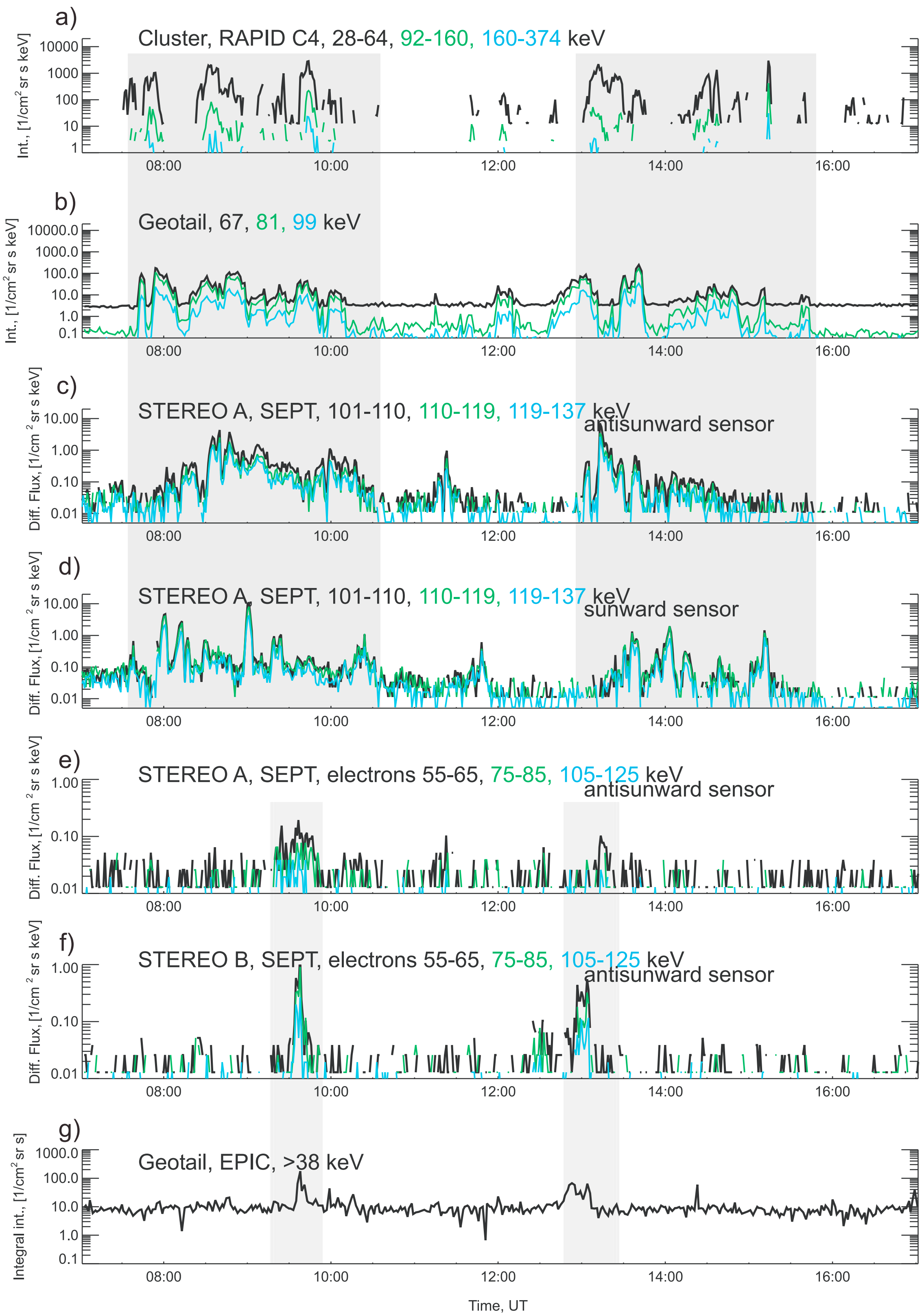

Figure 4. Proton intensities observed by (a) Cluster, RAPID and (b) Geotail, EPIC; ion differential flux measured by (c) STEREO A, SEPT (antisunward sensor) and (d) STEREO A, SEPT (sunward sensor); electron differential flux observed by (e) STEREO A, SEPT (antisunward sensor) and (f) STEREO B, SEPT (antisunward sensor); and (g) electron integral intensities measured by Geotail, EPIC on 18 January 2007. Vertical transparent bars denote upstream ion events (wide) and the electron bursts (narrow). The *AE* index during this time interval was almost always >200 nT.

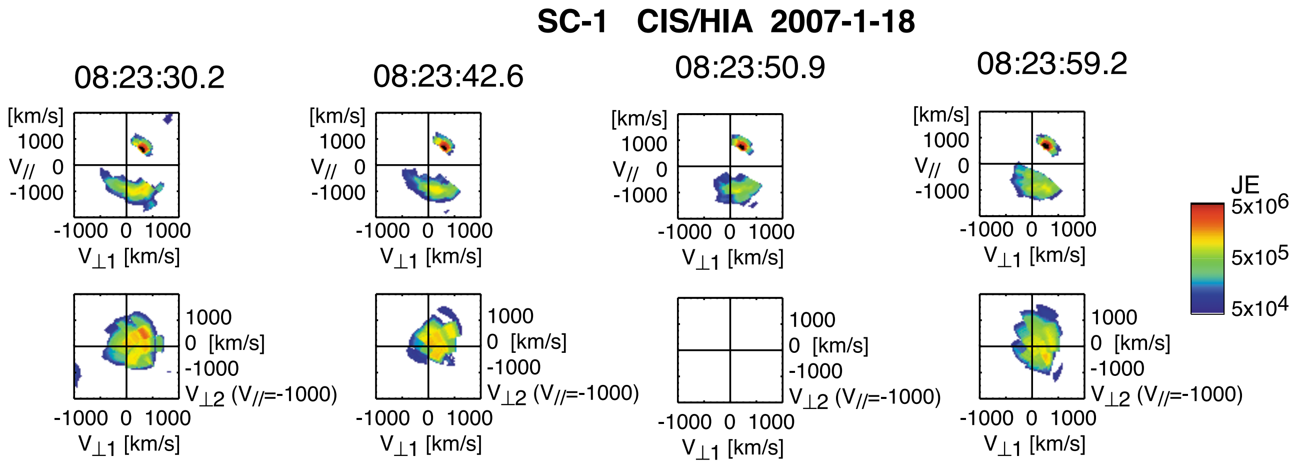

Figure 5. (top) Cross sections of 3-D ion distributions in the $V_{\perp 1}$ versus $V_{\|}$ velocity space measured by Cluster/CIS/HIA. Here $V_{\|}$ and $V_{\perp 1}$ are the velocity components parallel and perpendicular to the magnetic field. The plane of the cross section is defined along the magnetic field and the solar wind bulk velocity vector. (bottom) In order to check the gyrotropy, the 3-D ion distributions in the $V_{\perp 1}$ versus $V_{\perp 2}$ velocity space are plotted, where $V_{\perp 2}$ is the velocity component perpendicular to the magnetic field for the cross section at $V_{\|} = -1000$ km s^{-1} (since the back-streaming ions are found at $\sim V_{\|} = -1000$ km s^{-1} in the $V_{\|}$ versus $V_{\perp 1}$ plot).

the recovery phase of geomagnetic substorms are always accompanied by energetic electron bursts at energies >30 keV. At the same time Fermi (or diffusive) acceleration cannot explain the presence of >30 keV electrons. In order to be confident that electrons are of magnetospheric origin we checked the flow direction of these electron bursts. For this purpose we used the Geotail/EPIC electron integral flux data for the energies higher than 38 keV and Cluster/RAPID/IES electron fluxes at energies from 37 to 68 keV. In all cases electrons were flowing in the mainly sunward-dawnward direction. From these 65 events associated with electron bursts, in about 40% of the cases (~26 events) the electron bursts are also observed far upstream at STEREO A. For an electron burst at STEREO A we required that enhancements of the flux be at least 2 times and in several adjacent energy channels. The percentage of the upstream events associated with the electron bursts (56%) is lower than in studies by *Anagnostopoulos et al.* [1999] and *Christon et al.* [2000] who got ~80% and ~75%, respectively. One reason could be a stricter definition of what is the “electron burst”: in our study we require that for an electron burst the electron flux (the integral flux in the case of Geotail/EPIC measurements) should be at least 2 times higher than the background. While in study of *Anagnostopoulos et al.* [1999] it is at least 1.5 times higher. Another reason is that the >220 keV electrons studied by *Anagnostopoulos et al.* [1999] have larger gyroradius and have easier access to the upstream region. Additionally we demand at least 2 subsequent measurements for one burst (at time resolution 96 s for EPIC data and 1 min for IES). Also different solar activity during the observations and different instrument sensitivity could lead to the difference between observations.

[25] In 84% of the cases (~55 out of ~65 events), observation of electrons in front of the bow shock is related to the increased *AE* index (>200 nT) which primarily reflects auroral geomagnetic activity and is typically associated with substorm activity. In 77% of the events during which electrons were not observed the *AE* index was also <200 nT, indicative of a quiet magnetosphere.

[26] For the events observed by Geotail with magnetospheric activity, nonexponential spectra in the energy range from 77 to 526 keV (close to a power law) are often observed. We note that this energy range is well above that of diffuse ions accelerated at the shock, where the effective cut off at ~200–330 keV is observed when there is no preexisting seed population [*Meziane et al.*, 2002].

[27] We also examined the presence of oxygen upstream of the terrestrial bow shock using the Geotail/EPIC/STICS data. According to *Keika et al.* [2004] the observations of

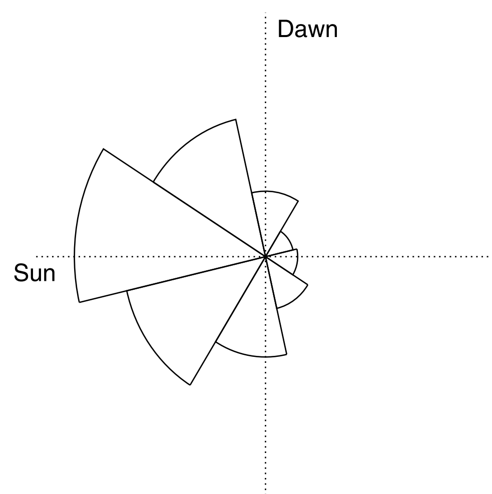

Figure 6. Distribution of the integral electron intensity in eight directions on 18 January 2007 at 0937 UT (flow not look directions). The magnetic field was directed mainly toward the electron flow; therefore, the flow is mainly antiparallel to the magnetic field.

Table 1. Summary of the Statistical Study

Characteristic of the Ion Event at STEREO A	Total Number of Investigated Events	Percentage With the Given Characteristic
Association with electron bursts observed by Cluster/Geotail	117	~56% (65 events)
Simultaneous observations of electron bursts at STEREO A and Cluster/Geotail	65	~40% (~26 events)
Association with *AE* index > 200 nT and electron bursts	65	~84% (~55 events)
Association with *AE* index < 200 nT and absence of electron bursts	52	~77% (~40 events)
Association with O^+ observed by Geotail[a]	84[b]	~29% (24 events)
Observations of O^+ and/or electron bursts	117	~57% (67 events)

[a]Number of counts per event > 3.
[b]Here we consider events during which the observations by Geotail/EPIC were available and spacecraft was upstream the Earth's bow shock.

low-charge-state heavy ions (like ionospheric ion O^+) are associated with magnetospheric leakage and depend on the geomagnetic activity. From the 117 events we choose for the composition analysis those during which Geotail/EPIC data were available (84 time periods). For the analysis we took only time periods when proton intensities observed by the EPIC instrument during an upstream event were approximately constant for at least 20 min, i.e., without flux level changes which occur due to the variable connection of IMF to the bow shock. If an upstream event consists of several subevents due to changes in the interplanetary magnetic field we choose the longest in duration. We use omnidirectional count per event data at the energies from 55.74 to 212.14 keV/e for O^+. The omnidirectional count is integrated throughout the event duration and for all corresponding energy channels. The O^+ counts are zero when no upstream event occurs; that is, the background in the heavy ion channel is less than the one count level. We therefore require more than 3 counts per event to take statistical fluctuations into account [see also *Keika et al.*, 2004]. We classify events as of magnetospheric origin when O^+ counts per event >3. Based on this criteria, from 84 time periods, we obtained 24 events of magnetospheric origin. 92% of events with presence of low-charge-state oxygen are associated with the sunward flowing electrons, and ~83% additionally with *AE* index >200 nT.

[28] Resuming section 3.2, we conclude that 57% of all ion events (67) near the bow shock are with strong evidence of a magnetospheric contribution as electron bursts and/or the presence of O^+ are observed. However, we cannot exclude the presence of solar wind ions accelerated at Earth's bow shock during these events, as 34% of all upstream energetic ion events (~40 out of 117 events) are associated neither with the electron bursts nor with high magnetospheric activity. A summary of the statistical characteristics of the upstream events observed far upstream by STEREO A in association with the bow shock/magnetospheric activity is presented in Table 1.

3.3. Association of Energetic Particle Upstream Events With the Magnetic Field Connection to the Bow Shock

3.3.1. Statistical Study

[29] Now we examine whether the energetic upstream events observed by *Desai et al.* [2008] are magnetically connected to the terrestrial bow shock. In such cases it is reasonable to assume that the Earth's bow shock may serve as an accelerator of particles to suprathermal energies or that the particles have escaped from the magnetosphere.

[30] To check the magnetic field connection we consider two methods. The first method tests if the magnetic field line

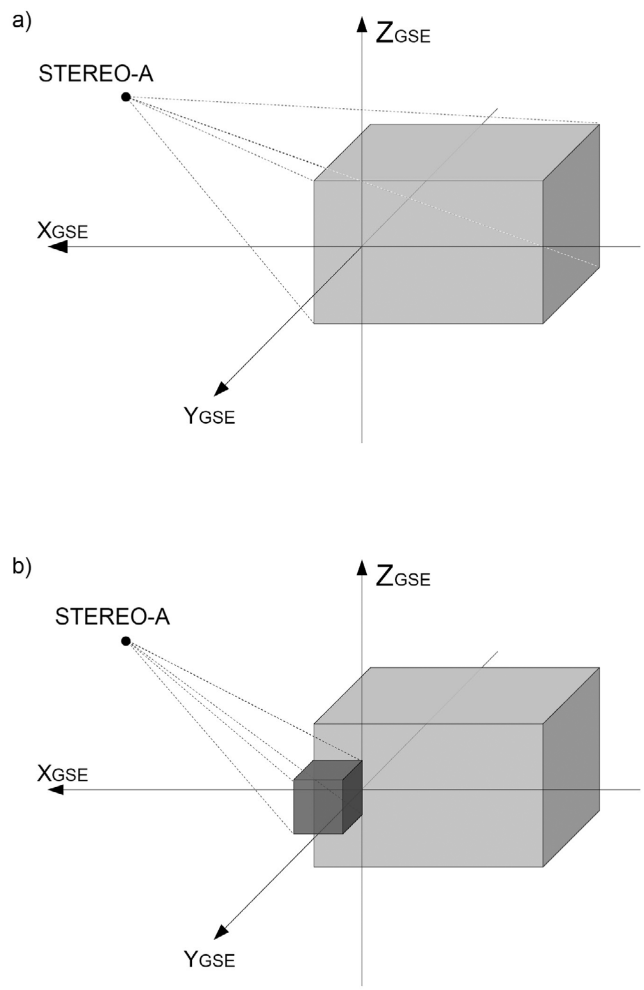

Figure 7. (a) A sketch of how the view direction at STEREO A was defined. In light grey we denote a box which covers the bow shock from the dawn side. The black dot shows the position of the STEREO A satellite. The dashed lines define the boundaries of the view direction in which the magnetic field vector is likely to be connected to the bow shock. (b) The same box from the dawn side and additionally a dark grey box which represents the bow shock from the dusk side. The box from the dusk side has substantially smaller size because STEREO A is located at the dawn side relative to the Earth, and magnetic field lines can be connected to the dusk part of the bow shock only in this small region.

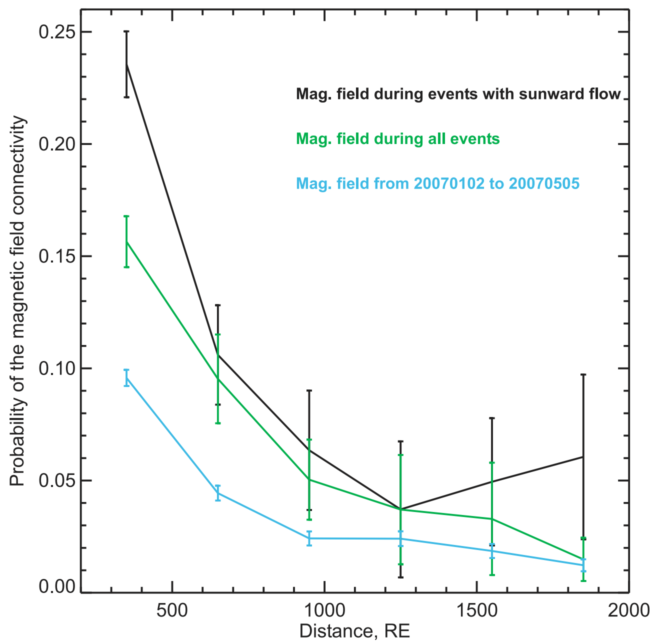

Figure 8. Probability of the magnetic field connectivity to the terrestrial bow shock versus radial distance from the Earth toward the Sun, in GSE. The plot is constructed by binning the data into intervals with 300 R_E width. The blue line corresponds to the probability of the magnetic field observed by STEREO A to be connected to the terrestrial bow shock for the time period from 2 January to 5 May 2007. The probability of the magnetic field connectivity to the terrestrial bow shock for time periods when the energetic events were observed by STEREO A is denoted by a green line, and those from these events which have sunward particle flow are denoted by a black line.

from STEREO A crosses the bow shock surface. In this case the magnetic field vector observed by STEREO A is extrapolated as a straight line to the bow shock surface. The shape of the bow shock surface is derived using the method by *Peredo et al.* [1995] and modified for the corresponding solar wind conditions [*Spreiter et al.*, 1966].

[31] For the second method, we define the view direction at the STEREO A that covers the bow shock. We assume that the bow shock is a box (i. e. the view direction is a quadrangular pyramid), of the size XGSE = [−200, 30] R_E, YGSE = [−100, 30] R_E, ZGSE = [−130, 130] R_E and at the dusk side, when YGSE > 0 then XGSE = [30, 0] and ZGSE = [−35, 35] R_E (i.e., the box is smaller; this is done because the STEREO A is located at the dawn side), see schematic representation in Figure 7. Then we check if the direction of the observed magnetic field is within the calculated view direction. This is done for each data point. The size of the box is defined from the statistical investigation of the bow shock surface crossings by the magnetic field observed at STEREO A using the first method. The size of the box (at least at the dawn side) is somewhat bigger than the actual surface of the bow shock. Using a box with a size slightly larger than the bow shock surface we already include some scattering of the magnetic field due to the convection and rotations. Due to the dynamical behavior of the solar wind the direction of the IMF observed at STEREO A is not necessary the same as the IMF at the bow shock. Also we assume here that the upstream region in the vicinity of the bow shock is a source of particles and waves. Thus it is not necessary for the magnetic field to be connected directly to the bow shock surface but magnetic connection to the upstream region is sufficient.

[32] Both of these models show similar results for magnetic field connectivity, although the first is slightly stricter. We chose the rectangular box method because the numerical algorithm to find a solution of the crossing the three-dimensional surface by line does not always converge.

[33] We conducted a statistical study as the magnetic field during events often rotates, and it is hard to correlate the magnetic field connectivity for each individual event. Unlike *Scholer et al.* [1980b] for example, we neglect magnetic field convection.

[34] First we took all magnetic field measurements with 1 min resolution by STEREO A for the time interval used

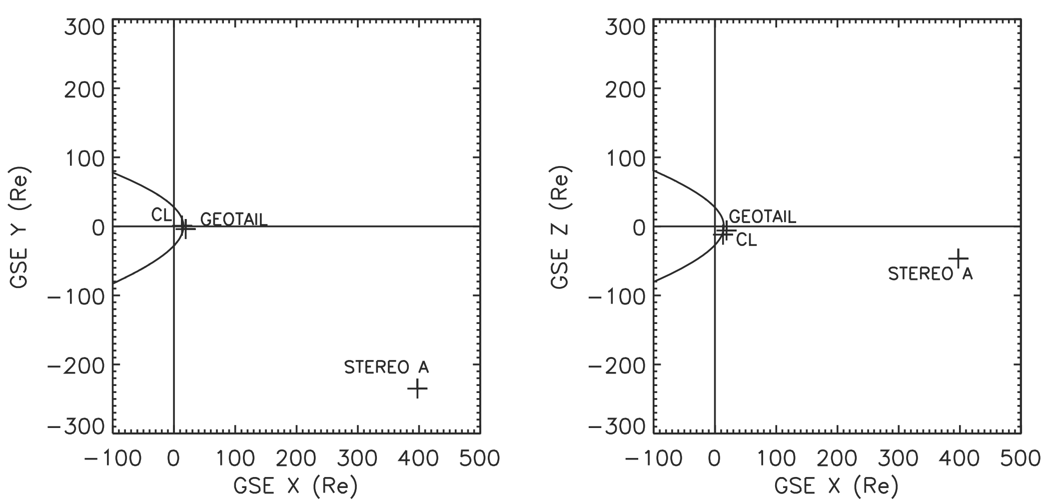

Figure 9. Projections of STEREO A, Cluster 4 (~13.2, ~1, ~−12 R_E GSE), Geotail (~19, ~−4, ~−6 R_E GSE), and the bow shock locations onto the (left) X-Y and (right) X-Z planes in GSE, during the event on 9 February 2007, ~0130 UT.

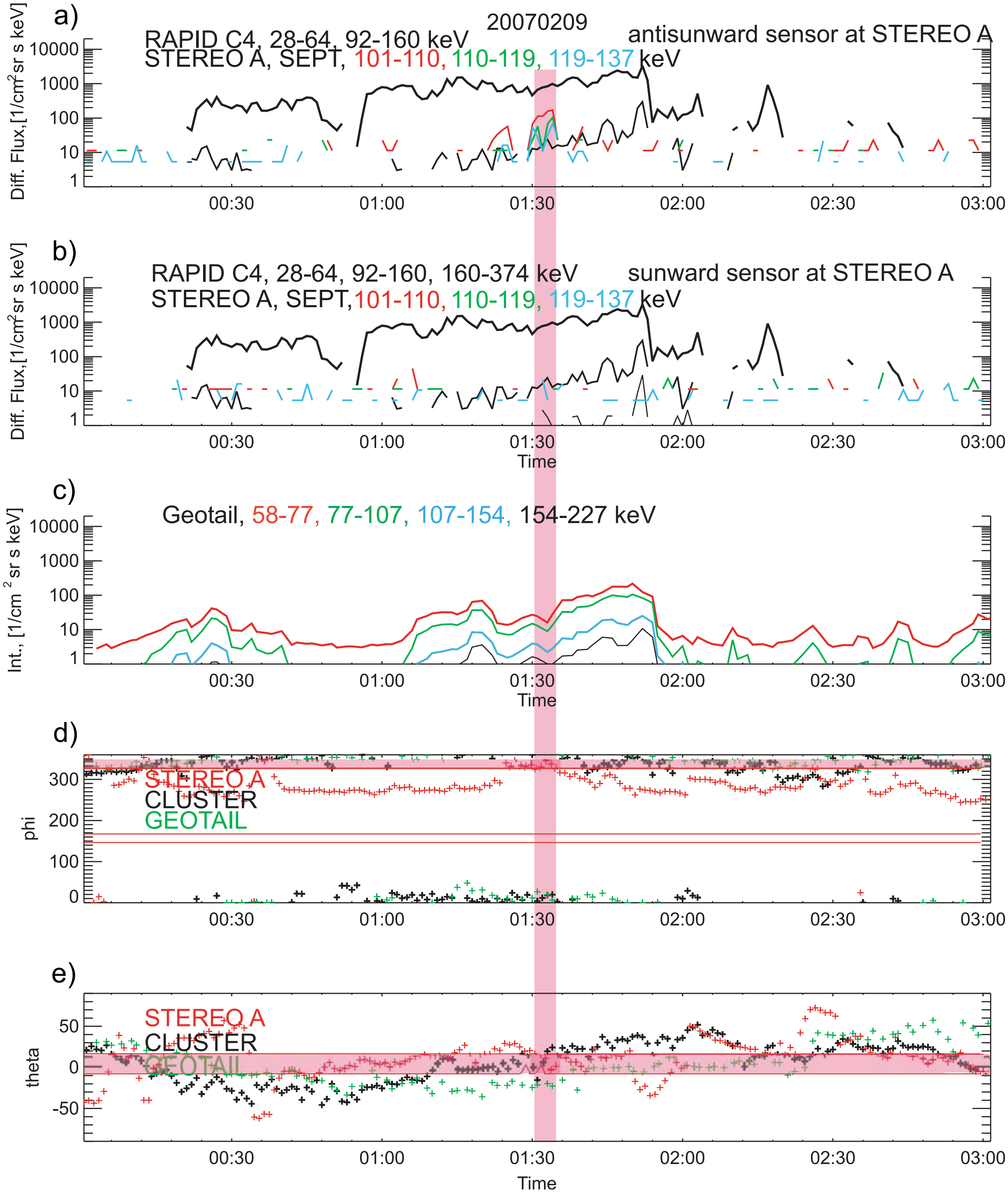

Figure 10. Ion fluxes of (a) STEREO A, SEPT (antisunward sensor) and (b) STEREO A, SEPT (sunward sensor) in the energy range of 101–137 keV (red, green, and blue lines) and the proton intensities of Cluster, RAPID, 28–160 keV (black lines); (c) the proton intensities of Geotail, EPIC, 58–227 keV; (d) the azimuth angle phi of the magnetic field in spherical GSE coordinates for the Cluster/FGM, STEREO A/IMPACT, and Geotail/MGF data; and (e) the same for the polar theta angle on 9 February 2007. The horizontal red transparent bars in Figures 10d and 10e denote the range of the magnetic field direction which is favorable for the connection to the bow shock. The vertical red transparent bar marks the time period when the magnetic field at STEREO A was connected to the terrestrial bow shock.

(from 2 January to 5 May 2007) and calculated the probability of the magnetic field connectivity from STEREO A to the bow shock. The probability is defined as the ratio of number of the magnetic field vectors which are connected to the bow shock divided by the number of all magnetic field vectors. The results are shown in Figure 8 (blue line). As expected, the probability of magnetic field connectivity falls off with increasing radial distance from the Earth. Next we

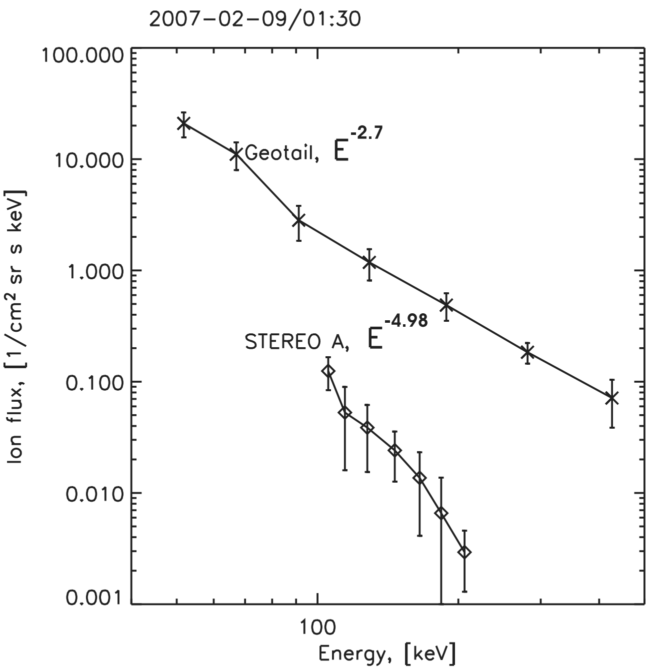

Figure 11. Energy spectra for STEREO A/SEPT, antisunward ion flux, and Geotail/EPIC omnidirectional proton intensity on 2 February 2007, ~0130 UT. The spectral index is determined for the Geotail data for the energy range from 46 to 523 keV and for the STEREO data from 101 to 220 keV.

select from the *Desai et al.* [2008] data set the 145 upstream events with at least 1 hour duration observed by STEREO A (in this case the simultaneous observations with other spacecraft unnecessary) and carried out the same procedure only for the time periods during which the upstream energetic ion events were observed (number of the magnetic field vectors during events which are connected to the bow shock divided to the number of all magnetic field vectors during the upstream events). The statistical study shows that the events are positively correlated with magnetic connectivity to the bow shock (green line in Figure 8). The probability of magnetic field connection to the bow shock is at least two times higher during the occurrence of events than during the total time period. Next, we refined our selection by choosing only those events at STEREO A which have directional flow anisotropy of the particle flux (1st channel, 101–110 keV) greater than 1; that is, flow is sunward (103 time periods). The directional flow anisotropy is calculated as the ratio of particle flux measured by the antisunward sensor (sunward flow) to the flux measured by the sunward sensor (antisunward flow). The probability of the magnetic connection for these events is larger, see the black line in Figure 8, especially for the events from 200 R_E to 500 R_E. Beyond 500 R_E the statistical errors are so large that the difference between black and green lines is not statistically significant. To estimate the error we use here the Bernoulli distribution for the high number of observations. Using the three sigma rule, with the confidence level of 95% we can say that the energetic events observed by STEREO A up to a distance of 1000 R_E are related to the connectivity of the magnetic field to the bow shock as the probability of the magnetic field connectivity during the events (black and green lines) is higher than during the total time period (blue line).

3.3.2. Event Example

[35] As an example, we present an event observed on 9 February 2007 at ~0130 UT when STEREO A was located at 464.5 R_E away from the Earth [397.5, −235, −46.6] R_E GSE. The locations of STEREO A, Cluster and Geotail are shown in Figure 9. In Figure 10 the proton fluxes measured by the antisunward SEPT sensor on STEREO A, by Cluster and by Geotail are shown. We can see that Geotail which was also located in the upstream region of the terrestrial bow shock observes an increase in ion fluxes during the same time period as observed by Cluster. Geotail observes more pronounced intensities than Cluster. However, this may be an artifact of the detector's inoperative central head-on Cluster.

[36] Additionally, Figure 10 shows the azimuthal angle phi and polar angle theta of the magnetic field vector in spherical GSE coordinates from the Cluster and STEREO A data, and the connection of the magnetic field measured at STEREO A to the terrestrial bow shock. The red horizontal stripes in Figures 10d and 10e show the angles phi and theta at which the magnetic field observed by STEREO A most probably was connected to the terrestrial bow shock (here the box model described in section 3.3.1 was used). The vertical colored bar indicates the time period when the direction of the magnetic field at STEREO A lies within both of these red areas, i.e., simultaneously for the phi and theta angles. Thus we see that when the magnetic field measured by STEREO A is connected to the bow shock we observe an energetic ion event only by the antisunward sensor (i.e., sunward flow) at STEREO A. The sunward-looking sensor does not observe any increase of the fluxes. Therefore the ion flow observed at STEREO A is highly anisotropic and sunward directed. During this entire time interval there is no other period with favorable magnetic connection to the terrestrial bow shock.

[37] The spectra during this event are presented in Figure 11. It shows that at Geotail the spectral shape of the proton distribution in the energy range from 77 to 523 keV is a power law. At STEREO the distribution is reasonably well fitted by power law with a steep slope. We would like to note that the spectrum at Geotail is harder than at STEREO A. In most cases we observe that the spectrum is harder at great distances as the lower-energy particles are preferentially scattered out of the beam. This is a rather untypical case but not a unique one.

[38] During the time period from 0105 to 0155 UT, O^+ ions were observed by Geotail implying at least partly magnetospheric origin of this event.

[39] In this example, we have shown that (1) Cluster and Geotail observe particles for a substantially longer time; (2) the event at STEREO A appears only when magnetic connection to the bow shock is established; and (3) the sunward flowing ions at STEREO A are associated with the sunward directed electron burst (not shown here). We have also shown (4) the presence of the O^+ ions at Geotail and (5) the power law proton spectra close to the bow shock. We conclude that the representative event of 9 February 2007 observed around the same time by Cluster, Geotail and STEREO A both near and far from the bow shock is at least partly of magnetospheric origin.

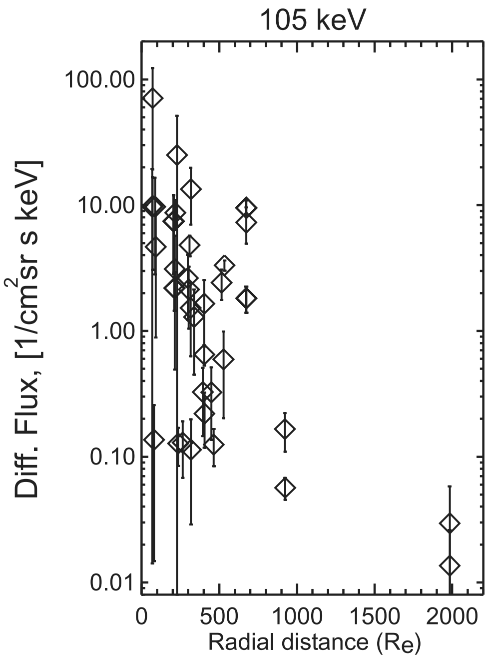

Figure 12. The differential fluxes of sunward flowing upstream ions measured by STEREO A and STEREO B for the energy range 101–110 keV versus radial distance.

3.4. Ion and Electron Intensities During Upstream Events

3.4.1. Ion Intensities

[40] As shown in section 3.3, the connection of the magnetic field to the terrestrial bow shock is important for energetic upstream ion events. Hence, the following scenarios are possible: (1) the energetic particles originate from magnetosphere; (2) energetic field-aligned ion beams are generated and accelerated at the shock; and (3) CIR-associated ions are accelerated by multiple scatterings between the large-amplitude Alfvén waves themselves and the Earth's bow shock in very large regions (of the order of ~700 R_E) [*Lin et al.*, 1974; *Desai et al.*, 2008].

[41] For the first two scenarios we would expect to observe higher intensity at the Earth's bow shock than further away. If energetic ions were associated with a CIR, the falloff of the ion intensity would not be observed. Therefore we plot the average ion fluxes in our events (here most clear events were chosen), see Figure 12. The fluxes fall off with the radial distance, implying that most of the events have higher intensities near the Earth's bow shock and are most likely originating from the direction of the terrestrial bow shock and not an internal CIR feature.

3.4.2. Electron Intensities

[42] Ion upstream events accompanied by energetic electrons (>75 keV) are associated with the magnetospheric origin [*Scholer et al.*, 1981; *Anagnostopoulos et al.*, 1999; *Christon et al.*, 2000]. However, electrons are also observed in association with CIRs [*Simnett and Roelof*, 1995; *Roelof et al.*, 1996]. We examined observations by STEREO A when the spacecraft was at >8500 R_E from the Earth toward the Sun, in 2008. They show that the typical intensity of the short-duration electron bursts at 65–75 keV is about 0.07 and maximum about 0.1 [cm^2 s sr keV]$^{-1}$. During the upstream event at Cluster on 18 January 2007, RAPID/IES data show that the electron intensity during the burst equals 8 ± 3 [cm^{2}s sr keV]$^{-1}$ at 50 to 68 keV. The intensity observed by STEREO B during the same event is substantially lower than observed close to the bow shock 0.6–0.9 [cm^{2}s sr keV]$^{-1}$ and even lower at STEREO A, to ~0.2 [cm^{2}s sr keV]$^{-1}$ at 65–75 keV, see example in Figure 4. The intensity values observed by Cluster for the electron bursts are higher than the values for the electrons in the solar wind. As shown in STEREO A data for 2008, the strong short-duration spikes are not present when the spacecraft moves far from the Earth. Therefore, we consider that the electrons observed upstream of the terrestrial bow shock are of magnetospheric origin and that their presence is a good indicator of the magnetospheric origin of the events associated with them.

4. Summary and Conclusions

[43] Upstream ion events observed at STEREO A are indeed associated with the upstream events near the Earth's bow shock observed by Cluster and Geotail. The magnetosphere during most of these events was geomagnetically active and likely to be responsible for sunward flowing electron bursts. A statistical analysis of the magnetic field connection to a broad region upstream from the bow shock and the appearance of the events has shown a positive correlation. The ion fluxes fall off with distance from the magnetosphere implying that the ions originate from the Earth's environment. These ion events are likely to be at least partly of magnetospheric origin, as the associated events at the Earth's bow shock (1) coincide with the sunward directed electron bursts, (2) are related to the high *AE* index, (3) have nonexponential proton spectra, and most important (4) show the presence of magnetospheric/ionospheric O^+ ions. Furthermore, 57% of all ion events near the bow shock exhibit strong evidence for a contribution of magnetospheric origin as electron bursts and/or the presence of O^+ are observed and ~40% of the latter events are associated with electron bursts at STEREO A.

[44] Therefore, according to this and to the earlier studies [e.g., *Keika et al.*, 2004] magnetospheric leakage ions are not permanent feature upstream of Earth's bow shock. They mainly appear when Earth's magnetosphere is disturbed (e.g., high *AE* index). For many cases in our study the passage of CIRs triggered the magnetospheric substorms and ions were released from the magnetosphere. Hence, the CIRs play an important role in activation of upstream events presumably due to easier radial scatter-free propagation of the ions and to easier generation (acceleration during substorms). However, the presence of solar wind ions accelerated at Earth's bow shock during these events is not excluded, as 34% of all upstream energetic ion events are associated neither with the electron bursts nor with high magnetospheric activity. Nevertheless, these events usually are less intense. Only during the upstream events associated with magnetospheric bursts is STEREO able to observe the strongest upstream ions when connected to the magnetosphere/bow shock.

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