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Association of Low-Charge-State Heavy Ions up to 200 R_e upstream of the Earth's bow shock with geomagnetic disturbances

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[1] We present the first study of Low-Charge-State Heavy Ion (LCSHI) events covering a region from Earth's bow shock to the L1 point, obtained with the Suprathermal Ion Composition Spectrometer onboard Wind. STICS is capable of distinguishing charge states of suprathermal ions. In 1995–2000 we found a large number of particle events revealing species of magnetospheric origin. LCSHI events tend to occur in series and in connection with geomagnetic activity. The occurrence rate is found to increase towards solar maximum. The spatial region covered by this particle population ranges from the bow shock to beyond distances of 130 R_e, where one of the strongest events occurred. Based on the characterization of LCSHI events we discuss mechanisms for their formation. We conclude that the most probable sources of these ion events are substorms in association with Alfvén waves in high-speed solar wind streams and the magnetic storm recovery ring current. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2788 Magnetospheric Physics: Storms and substorms; 2116 Interplanetary Physics: Energetic particles, planetary; 2154 Interplanetary Physics: Planetary bow shocks

1. Introduction

[2] An O^+ event detected by *Möbius et al.* [1986] indicated that Low-Charge-State Heavy Ions (LCSHI) are transported sunward of the Earth's bow shock. Elements in the solar wind are typically highly charged (e.g., O^{6+}, O^{7+}). There are of course low-charge-state ions carried with the solar wind in the form of pickup ions that originate from the interstellar source [e.g., *Geiss et al.*, 1995] and the inner source [e.g., *Schwadron et al.*, 2000]. However, these sources are distributed and do not produce event-like signatures. The LCSHI composition, low charge-state, event-like nature, and proximity to Earth's bow-shock suggest a terrestrial ionospheric source. Recently, *Christon et al.* [2000] presented a study of LCSHIs observed with Geotail/EPIC/STICS [*Williams et al.*, 1994] close to the bow shock. They found more than 500 intervals with O^+, N^+ and O^{2+} ions in 1995–1998. The orbital characteristics of the Geotail spacecraft however limit this data set to an upstream distance of less than 30 R_e from the Earth and to relatively short time intervals (days) that Geotail spent at one time in the region upstream from the bow shock. LCSHI events form distinct upstream particle populations complimentary to bow shock associated populations. The latter were most recently characterized in detail by *Desai et al.* [2000] based on Wind observations of ions with energies ≥30 keV/nucleon. In their study it was not possible to distinguish ionospheric origin events from upstream events of solar wind origin since charge states were not identified. With the Wind/SMS/STICS [*Gloeckler et al.*, 1995] dataset we are able to extend the observational domain of LCSHI events from earlier studies in spatial scales and, more importantly, reveal conditions that are typical for LCSHI event emergence which narrows the spectrum of possible sources.

2. Instrumentation and Observations

2.1. Wind/STICS Observational Constraints

[3] The Suprathermal Ion Composition Spectrometer of the Wind spacecraft consists of an electrostatic deflection system that allows only ions with a certain energy-per-charge, E/q, (6.2–223.1 keV/e) to enter the detector. Ions are then led to a time-of-flight (TOF) section that consists of thin carbon foils and microchannel plates, triggering a start and a stop signal. The ions' total energy, E, except for losses in the carbon foils and in the dead layer of the solid state detector (SSD)(~30 keV), is measured subsequently. The combination of E/q, TOF and E measurements allows determination of the mass and charge of the ions. Since the E/q is determined by the instruments' deflection system low charge corresponds to low total energy. Therefore most LCSHIs have a total energy below the SSD threshold resulting in no total energy measurement. This event type, classified as a double coincidence event with a given E/q and TOF, requires only a start and stop signal in a given coincidence window. However, energetic particles penetrating the detector housing are a significant source of background for double coincidence measurements. To filter out the background we excluded time periods for which Wind observed He intensities in the energy range 3.2 MeV/n – 6.2 MeV/n that exceeded 0.01/(cm^2 s sr MeV/n).

[4] Another time-dependent source of background present in the Sun-facing sector are suprathermal protons. For our survey we excluded this sector from analysis. For the most part we see O^+ particles entering from the antisunward facing sectors. With these techniques we reduce the background almost entirely. To identify LCSHI counts as events, we require more than 3 O^+ and N^+ particles per hour from the upstream hemisphere. Based on this classification scheme we observed a total of 162 upstream LCSHI events in 6 years of observations more than 10 R_e upstream of the bow shock with a total of 1345 days (or 61%) coverage.

2.2. LCSHI Event Studies

[5] In order to characterize upstream LCSHI events from the orbit of Wind, we show in Figure 1 STICS observations along with the DST index and in situ solar wind data by the Wind Magnetic Field Investigation [*Lepping et al.*, 1995] and Solar Wind Experiment [*Ogilvie et al.*, 1995]. The top two panels reveal a typical series of LCSHI events observed by STICS. Only certain DST events are associated with LCSHI events. The bottom two panels indicate the presence of compression regions on Sep. 22 and Sep. 26. Only the Sep. 26 compression, caused by a Corotating Interaction Region (CIR), is followed by a series of LCSHI events, although both apparently triggered DST events. The fast solar wind stream driving the Sep. 26 compression carries outward IMF

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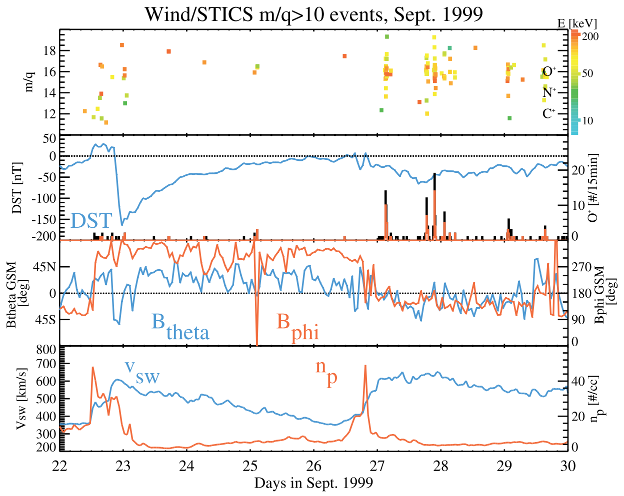

Figure 1. Example of a series of upstream LCSHI events in Sep., 1999. The top panel shows WIND/STICS sunward streaming suprathermal ion counts in the m/q range 10 to 20, color coded to indicate the ion's energy. The second panel depicts a histogram of the number of ions falling in the O^+ category accumulated in 15 minute bins. The fraction of these ions entering the sensor facing the antisunward direction is marked in red, in comparison to the total number marked in black. The DST index is shown in blue. Azimuthal (blue) and elevation angle (red) of the IMF in GSM coordinates are shown in the third, solar wind proton density and speed (red and blue) are shown in the bottom panel.

polarity. The Russell-McPherron effect (R-M) [*Russell and McPherron*, 1973] takes into account the relative angle between the Earth's dipole axis and the ecliptic plane. It predicts that sunward (antisunward) IMF in March (September) leads to a southward B_z component in GSM coordinates, which favors magnetic reconnection. Shortly after the passage of the CIR compression, LCSHI events emerge in the fast solar wind stream. This example is one of 25 observed series of LCSHI events. It is representative for periods near solar maximum, when most of these events occur. The upstream LCSHI event occurrence depends upon both geomagnetic activity and southward B_z. Single events last up to about 1 h, but the on average 6 observed events per series continue as long as fast solar wind impinges on the magnetosphere. Only 11 of 162 total events are found to be isolated events.

2.3. Observational Distribution and Dependencies

[6] The top two panels of Figure 2 show the relative location of the Wind spacecraft with respect to the Earth's nominal bow shock in GSE cartesian coordinates for LCSHI events. A common feature of LCSHI events in the dawn sector is a significant non-radial IMF, suggesting that in general a magnetic connection to the bow shock is essential. We found LCSHI events quite far upstream (>100 R_e) as well as behind the Earth. The event frequency is shown in the bottom panel by color coded squares representative for Wind's location projected into the plane. For each square we provided the frequency of LCSHI event observations taking into account the in-situ time of observation. Due to incomplete coverage certain areas are left blank. Note that the statistical error is significant since the total number of events observed is low.

[7] The resulting image has implications for the global distribution of upstream LCSHI events. Highest event frequencies are reached in the vicinity of the bow shock consistent with the terrestrial origin. Typical IMF conditions vary about being quasi-parallel at the dawn side of the bow shock. Therefore more LCSHI events are observed dawnward of local noon. The majority of LCSHI events are observed northward of the ecliptic plane, which can be explained with a magnetic reconnection geometry. In Figure 3 we show probability histograms of relevant parameters for a) (solid lines) event periods measured upstream from the Earth's bow shock and b) (dotted curves) general conditions, along with temporal distributions and m/q histograms of LCSHI events during 1995–2000. Coverage is not complete since certain periods had to be excluded (e.g., energetic particle events, passages of the magnetosphere and sheath, incomplete sets of observations). Comparison of the event periods to general conditions shows that LCSHI events are more likely to occur during fast solar wind, low density, and enhanced geomagnetic activity periods, which typically follow CIR compressions. Hence CIR-associated fast streams are a likely trigger for LCSHI presence upstream of the bow shock. Typical conditions are more southward than average IMF, and a distribution about a more open Parker spiral angle which is typical for high-speed solar wind periods. This puts into perspective the *Christon et al.* [2000] claim of (<45° from) radial IMF during events, supposedly due to the more limited orbital range of Geotail. The temporal distribution of LCSHI events reveals more events in the rising phase of solar activity (1999) than near solar minimum (1995/1996), reflecting the solar cycle dependency of the magnetospheric O^+ abundance observed by *Young et al.* [1982]. Most events are observed following the autumnal equinox. A local maximum is also seen in March, stressing the relevance of the relative field geometries according to the R-M effect. This may also explain the higher probability of LCSHI events during out-

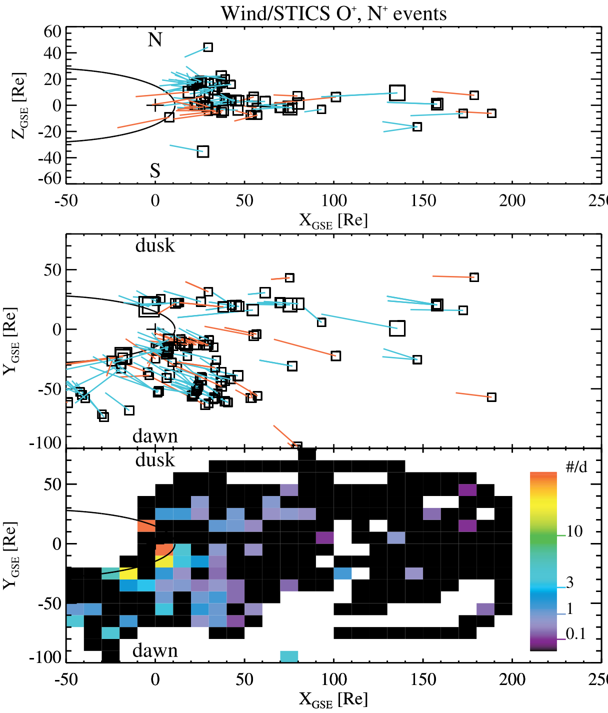

Figure 2. Distribution of Wind/STICS upstream LCSHI events 1995–2000 in the X_{GSE}/Z_{GSE} plane (top panel) and X_{GSE}/Y_{GSE} plane (lower two panels). The probable location of the bow shock is indicated with the black parabola. The top two panels depict event locations. The color coding indicates magnetic field direction: red is inward (sunward) and blue is outward. The length of red and blue lines in the top two panels is proportional to B_{mag}. Sizes of squares are proportional to the total sunward streaming LCSHI counts. In the lower panel color coding indicates the frequency of LCSHI events for a given 10 R_e × 10 R_e square in the X_{GSE}/Y_{GSE} plane normalized with the time Wind spends in a given volume. For clarity we omitted events that project into the region behind the bow shock.

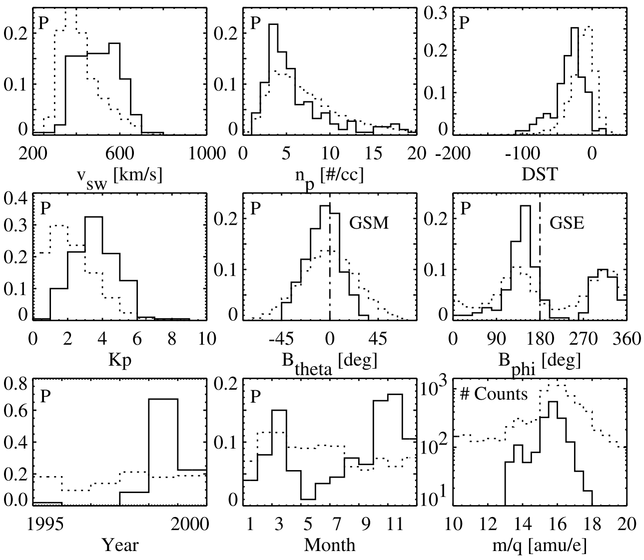

Figure 3. The top two rows of histograms display the probability for solar wind and geomagnetic conditions for all valid time periods 1995 through 2000 (dotted lines) and for LCSHI time periods (solid lines). The first two panels of the bottom row show how the LCSHI events are distributed over time (solid: LCSHI event probability, dotted: coverage). Histograms of m/q (solid: TOF and E determined, dotted: all TOF events) are also given. Note that the background is negligible for particles with known TOF and E (triple coincidences), allowing the identification of O^+ (m/q = 16) and N^+ (m/q = 14).

ward IMF (B_ϕ(GSE) = 140°–160°), which is currently not understood. The composition gives predominantly O^+ with some N^+ ($N^+/O^+ = 0.213 \pm 0.013$; $C^+/O^+ \leq 0.02$). The N^+/O^+ ratio is very comparable to that measured in the ring current by *Gloeckler and Hamilton* [1987].

3. Discussion and Conclusions

[8] The Wind/STICS data presented here extend well away from the bow shock (>100 R_e) as compared to other reports [*Möbius et al.*, 1986; *Christon et al.*, 2000] (<30 R_e upstream). LCSHI event observations cover a large region from the vicinity of the bow shock, even behind the Earth, out to the L1 point. Generally, events are observed on field lines that point toward the Earth's bow shock hence indicating a direct magnetic connection. The compositional signature and directionality of upstream LCSHI events clearly show an ionospheric origin. Typically, single events are part of event series that are closely related to geomagnetic disturbances. The initiation of these disturbances is most-likely related to CIR-associated high-speed streams with predominantly outward (anti-sunward) magnetic field orientation. LCSHI event series continue as long as the fast stream imposes an appreciable southward IMF. These trains of events are most probable in the months of the autumnal equinox, when the RM-effect leads to a southward B_z component for outward IMF.

[9] Despite the correlation of halo coronal mass ejections to energetic particle events we found indications that isolated events are occurring in connection with CMEs at Earth.

[10] Two possible sources of magnetospheric ions consistent with the upstream LCSHI characteristics are partial ring current populations and substorm injections. These two sources contain significant O^+ components that fall within the energy range of 10's to 100's of keV during active times (correlated with negative IMF B_z intervals). Both of these populations have access to the dayside magnetopause. Recent studies indicate that a partial ring current dominates during the main and early recovery phase of large magnetic storms with ions, moving along open drift paths, making one pass through the inner magnetosphere before encountering the dayside magnetopause [*Liemohn et al.*, 2001]. In fact, "flow-out" losses can exceed all other losses by more than a factor of 10 at these times. Dispersionless energetic particle injections in the inner magnetosphere are associated with the expansive phase of magnetic substorms [*Lyons et al.*, 1990]. These particles become dispersed in energy as they drift in local time around the Earth to the dayside – ions around the dusk side, electrons around the dawn side. Presumably both these types of ion populations can exit the magnetosphere at the subsolar reconnection site.

[11] In order to observe magnetospheric ions upstream of the dayside reconnection site, the Wind spacecraft must be located on field lines that map to the subsolar magnetopause. For this to occur, given Wind's orbit, there must be a significant radial component to the IMF, which precludes intervals of large negative IMF B_z. Magnetic storms (during which the ring current loss at the dayside magnetopause is predicted to be large) violate this criterion because they are associated with long-duration strong southward IMF. However, during the early recovery phase of the magnetic storm, the southward IMF weakens triggering ring current decay. During this time, Wind may cross field lines connected to the dayside merging region and observe the leakage of ring current ions. In fact, several strong LCSHI observations occur under magnetic storm recovery conditions.

[12] The bulk of the observed LCSHI events likely occur in association with substorm activity. Figure 1 shows a series of LCSHI events observed during an encounter between the Earth's magnetosphere and a high-speed stream. This is typical of events that formed the basis for the statistical study. Non-linear Alfvén waves, a characteristic feature of high-speed streams [*Tsurutani and Ho*, 1999], produce the rapidly fluctuating southward IMF component seen in the third panel. The magnetosphere has been shown to respond dramatically to the southward IMF components of these large amplitude Alfvén waves, which trigger chains of consecutive substorms called HILDCAA (high-intensity, long-duration, continuous *AE* activity) events [c.f., *Tsurutani et al.*, 1995]. At some time during each event, the southward B_z component will be small enough and the IMF radial enough for field lines passing through Wind to map to the dayside magnetopause. Substorms (and the amplitudes of the Alfvén waves) are most intense near the peak of the high-speed stream and decrease with decreasing solar wind speed. This is also true of the LCSHI events shown in the top panel. High-speed streams, associated with corotating interactions regions, can recur over one or several 27 day rotation periods producing recurring chains of substorm and LCSHI events.

[13] The predicted characteristics of LCSHI events at the Wind orbit are consistent with observations, which can be grouped into 25 chains of LCSHI events associated with high-speed streams and 11 isolated events, in-part associated with magnetic storm recovery phases. More detailed statistical studies supplemented by event studies and multi-spacecraft observations are needed to understand the magnetospheric processes responsible for LCSHI events.

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