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Use of Fe charge state changes as a tracer for solar wind entry to the Magnetosphere

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Abstract. We present a comparison of high charge state ion composition measurements from ACE located near the L1 point and POLAR in the mid-altitude cusp/cleft, during the 1-3 May 1998 CME event. Using the frozen in charge state of the solar wind origin Fe ions as a tracer, we demonstrate the connectivity between the ACE observations and the high latitude measurements from POLAR. The ion charge state distributions were observed to show abrupt changes with variations in the average charge state of Fe between +6 and +15 corresponding to changes in the coronal source temperature of $4x10^5$ to $2x10^6$ K. A good correlation between the measurements at L1 and in the cusp/cleft was found, indicating direct entry of solar wind material during periods of southward IMF. In addition there is possible evidence for delayed entry during a period of predominantly northward IMF that may indicate a less direct entry mechanism for this configuration.

1. Introduction

The study of composition and charge state changes during a solar event provides a unique way of tracing the propagation of solar wind material through the Sun-Earth system. Evidence for prompt entry of solar wind material to equatorial geo-stationary altitudes during the March 1991 storm was reported by [*Grande et al.*, 1996] based on data from the CRRES satellite. However, at that time there were no upstream monitors to provide information on the solar wind composition and charge state. In the ISTP era the situation has improved with WIND, and now ACE, providing almost continuous upstream solar wind ion composition measurements. WIND and GEOTAIL data have been used to investigate the correlation of high charge state Oxygen ratios at low latitudes [*Christon et al.*, 1998]. At these latitudes sub-storms are thought to be responsible for transporting the solar wind material inward from the tail reconnection site. The observed delays of 6 to 9 hours are a combination of the times for solar wind entry, propagation and the subsequent sub-storm process. In this study we present the first comparison of ACE ion composition data with measurements taken by POLAR at high latitudes in the region of the mid-altitude northern cusp/cleft where more direct entry of the solar wind is expected.

The solar wind ion charge states correspond to the "frozen-in" coronal ionization temperature at outflow and are unmodified during the collisionless propagation through interplanetary space to the Earth's magnetosheath [*Gloeckler et al.*, 1986]. By using high mass and charge state species that can be easily distinguished from the local magnetospheric and ionospheric ions, it is possible to estimate the coronal source temperature of solar wind material recently introduced into the magnetosphere [*Grande et al.*, 1996, 1997]. This technique can be extended to help study the timescales for entry of the solar wind plasma into the magnetosphere. The changes in the charge state due to variations in source temperature (either temporal or as a function of coronal location) can be traced through the system, independent of the energization processes undergone during entry into the magnetosphere. For this analysis we have used solar wind Fe ions as they provide the greatest variation in charge state as a function of changes in the source temperature [*Arnaud and Rothenflug*, 1985].

POLAR [*Acuna et al.*, 1995] was launched on 24th February 1996 into a 1.8 by 9 Re orbit at 86 degree inclination with an 18 hour orbital period. The CAMMICE/MICS instrument [*Wilken et al.*, 1992] on POLAR is a 1-D time-of-flight ion mass spectrometer with a swept electrostatic analyser accepting ions with mass per charge in the range 1-220 keV/e. The instrument has a look direction perpendicular to the POLAR spin axis which allows 2D angular distributions at one energy per charge setting to be taken every six second spin. A complete energy spectrum is accumulated over 32 spins. The ACE (Advanced Composition Explorer) spacecraft [*Stone et al.*, 1998] was launched on 25th August 1997 and was injected into a halo orbit about the L1 point in December 1997. The ACE/SWICS (Solar Wind Ion Composition Experiment) instrument [*Gloeckler et al.*, 1998] is designed to measure solar wind ions in the range 0.5-100 keV/e. SWICS determines a full Fe spectrum every 12 minutes.

2. Observations

The data were taken between May 1 and May 3, 1998. This was a period of high solar activity during which the first in a sequence of CMEs was detected leading to an extreme compression of the magnetosphere on May 4 [*Russell et al.*, 2000]. ACE was near the L1 point providing upstream monitoring of the solar wind and detected some of the most dramatic changes in the solar wind composition and charge state yet to be seen [*Gloeckler et al.*, 1999]. These included a significant enrichment of the Fe ions making this an ideal period to look for a corresponding response in the Earth's

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Table 1. Details of the POLAR cusp/cleft periods.

Period	Date	Start UT	End UT	Λ_1 (deg)	Λ_2 (deg)
1	May 1	10:30	13:00	80.3	85.9
2	May 2	02:30	07:00	73.3	82.0
3	May 2	20:00	03:00	75.8	85.4
4	May 3	13:30	16:00	76.4	83.3

magnetosphere. The plane of the POLAR orbit was close to the noon-midnight meridian with the spacecraft traversing from the dayside equatorial plasma sheet, through the mid-altitude northern cusp/cleft region and into the tail lobe. For this study the region that we associate with the cusp/cleft has been identified by intense ions in the 1-10 keV/e range accompanied by high mass and charge ions assumed to be of solar wind origin. During this three day period POLAR traversed regions matching these conditions on each of its four orbits. The intervals and their extent in invariant latitude (equatorial, Λ_1 and poleward, Λ_2) are listed in Table 1.

The POLAR CAMMICE data for the period from May 1, 1998 to the end of May 3, 1998 is shown in Figure 1. Figure 1a, shows the differential energy intensity spectrogram for all ions (dominated by H^+) in the range 1 to 220 keV. The spacecraft starts off in the northern tail lobe at the beginning of May 1, passing rapidly through the nightside plasma sheet and down to perigee over the southern pole at approximately 04:00 UT. It re-emerges into the dayside plasmasheet crossing the equatorial ring current at 05:00 UT, proceeding outbound to higher latitudes and entering the cusp/cleft region at 10:30 UT. The cusp/cleft region can be identified by the periods of dense soft ion (1-10keV/e) precipitation colour coded in red in Figure 1a. The spacecraft re-enters the low flux northern tail lobe at 13:00 UT. The sequence then repeats for the remaining orbits. Figure 1b is the energy per charge spectrogram for Fe events (all charges). These events are extracted from a special part of the CAMMICE data stream (direct events) that provides full characterization of each individual ion. These are then processed on the ground to obtain the mass, energy and charge and the subset corresponding to Fe ions extracted for this analysis. Due to telemetry limitations this information can only be returned on a sub-set of all ions detected and a mass priority selection system is used on-board to identify those events to be transmitted to the ground. This gives priority to the high mass events that would otherwise be swamped by the H^+ and He^{++} if a purely random selection were employed. An integration period of 30 minutes was required to achieve sufficient statistics for this analysis and this ultimately limits time scales that can be studied using this technique. The total number of Fe ions detected throughout the study period was just in excess of 6000. From Figure 1b we see that the majority of Fe ion observations coincide with the cusp/cleft region identified from Figure 1a and listed in Table 1. In Figure 1c the same data set is plotted as a pitch-angle time series. There are insufficient counts during Period 1 to identify any non-isotropic behaviour but the other three periods show field aligned distributions, with parallel streaming in the case of Period 2 and anti-parallel for Periods 3 and 4. In Figure 1d the Fe ions are split by charge state to produce a charge distribution time series that is then used to calculate an average Fe charge state (Figure 1e). These show significant variations of the Fe charge state on time scales of a few hours.

The SWICS instrument on ACE provided continuous measurements of the solar wind Fe charge state distribution throughout the study period. Figure 2 shows the one hour averaged charge state calculated from the ACE/SWICS data (solid line). The time scale has been corrected for the propagation time from L1 to the Earth based on the measured solar wind flow velocity, which ranged from 350 km/s to 650 km/s during this period (Figure 3). The SWICS data has good mass per change discrimination and a one sigma uncertainty of 0.2 in the average charge is obtained based on the stable data interval during May 1st. The average charge state data from POLAR/CAMMICE (from Figure 1e) has been superimposed for the four cusp/cleft periods to aid the comparison. Error bars indicating the statistical uncertainty in the mean charge state are also shown.

3. Interpretation

Throughout May 1, 1998 a fairly typical solar wind Fe distribution was observed (Figure 2). This had an average Fe charge state of +10 consistent with a source temperature of

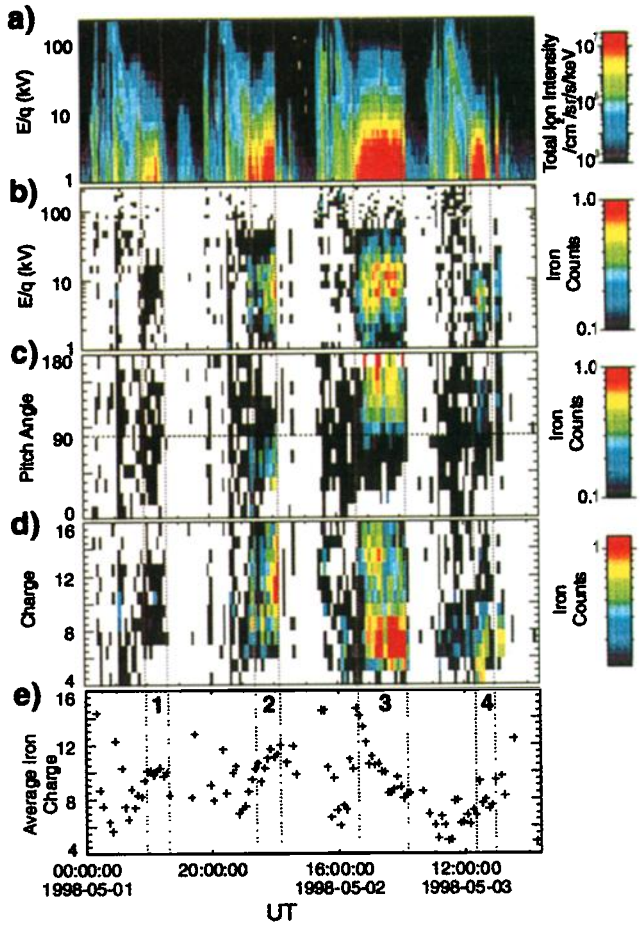

Figure 1. POLAR/CAMMICE plasma ion data for May 1-3, 1998. a) Total ion intensity, b) Fe count rate, c) Fe pitch angle, d) Fe charge distribution, and e) Average Fe charge. The numbered periods represent the four cusp/cleft crossings discussed in the text.

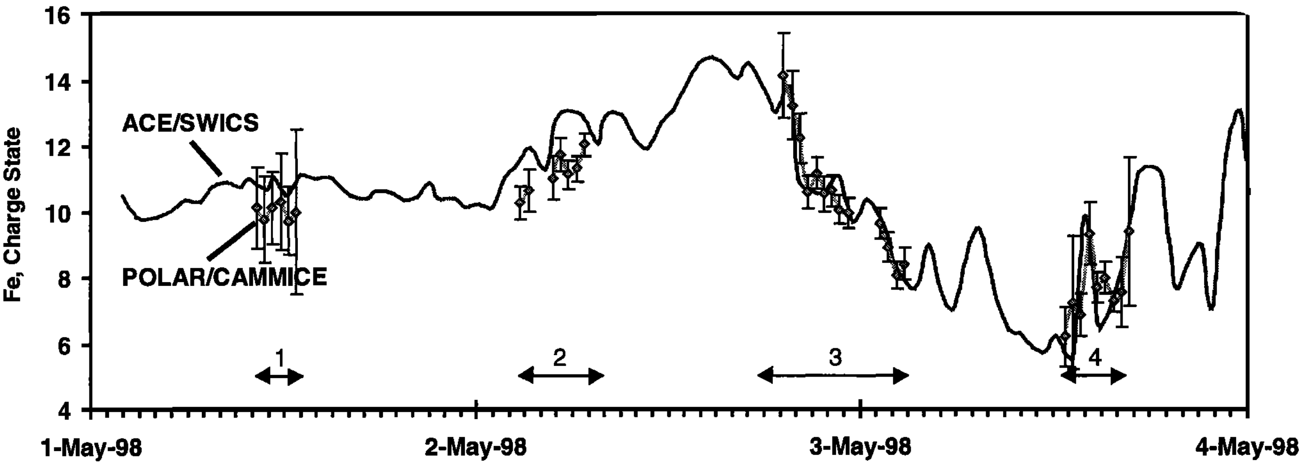

Figure 2. Average Fe charge state measured by ACE/SWICS at L1 between May 1 to 3, 1998. Times have been corrected for the propagation delay from L1 based on the observed solar wind flow velocity. Equivalent data from the POLAR/CAMMICE instrument is shown for the four LLBL/cusp traversals discussed in the text.

about 1.2×10^6 K. POLAR entered a weak cusp/cleft region (Period 1) at 10:30 UT. The average Fe charge state was slightly lower than that seen by ACE but due to the low number of Fe counts (a factor of 5 to 10 less than during the other periods), indicated by the large error bars, it is likely that the full distribution was not being adequately sampled. The observation was consistent with the peak in the ACE distribution of between +9 and +10 during this period. A sudden increase in the solar wind flow velocity was observed by ACE at 21:00 on May 1 (Figure 3) and was accompanied by increased structure in the B_Y and B_Z components of the IMF (*Skoug et al.*, 1999). This was consistent with a shock passing over the spacecraft related to a CME halo event observed by SOHO/LASCO on April 29th. The Fe average charge state at ACE remained constant until 01:00 UT on May 2. At which time ACE started to detect an increase in the average charge due to the introduction of a very hot plasma component with a coronal source temperature of several million degrees. POLAR entered the cusp/cleft (Period 2) shortly after the start of the increase seen by ACE and detected a similar enhancement. There was some discrepancy between the two measurements that could be the result of an additional delay in the transport of the plasma from ACE to POLAR of about 1.5 hours. During most of this period the IMF was predominantly northward such that reconnection in the northern tail lobe could account for a less direct entry to the cusp/cleft. However, this period between the shock and

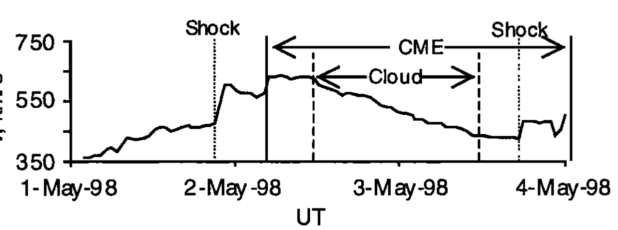

Figure 3. Solar wind velocity measured by ACE/SWICS between May 1, 1998 and May 4, 1998. The location of the Shock, CME and Cloud (taken from Skoug et al., 1999) are also shown.

appearance of a magnetic cloud type structure at about 12:00 UT, showed a highly structured IMF showing numerous southward turning events. The pitch angle for this period showed a generally field aligned distribution for the solar material consistent with a reconnected field line. The solar wind charge state continued to rise to a point at 14:00 UT on May 2 when it was dominated by the very hot component resulting in an average Fe charge state of just below +15. The geomagnetic effect of the CME resulted in an enhanced ring current, observed as an enhancement in the 100 keV proton flux during POLARs low latitude crossings just before and just after 16:00 UT (Figure 1a). The preliminary DST increased from 10:00 UT to a peak of -100 nT at 17:00 UT on May 2. At about 19:00 UT ACE observed a second much cooler distribution (Fe^{+7}), the transition between the hot and cold component took place over several hours during which a bi-modal distribution was observed. This coincides with Period 3 of the POLAR observations. By this time the IMF had changed to a southward orientation that would continue for the remainder of the study period. The average charge state from POLAR closely matched that observed by ACE (Figure 2) consistent with direct entry of the solar wind plasma into the cusp/cleft region. In addition, the bi-modal charge state distribution reported in the ACE results was also seen by POLAR (Figure 1d) corresponding to the mixture of hot and cold components within the magnetic cloud. Note that the large error bars at the beginning of Period 3 are a result of this bi-modal distribution. The pitch angle distribution of the Fe ions showed clear anti-parallel streaming of the population consistent with a tailward propagating mantle plasma [*Rosenbaer et al.*, 1975]. For both this and Period 4, the orbits were slightly pre-noon. This combined with the lack of field-aligned populations at the equatorial boundary indicates that the true cusp was not sampled in these two cases. By the time POLAR reached the final cusp/cleft crossing (Period 4) at 13:30 UT on May 3, the magnetic cloud had passed and the solar wind data was starting to show a recovery from the very cold component to a more typical solar wind distribution. As with Period 3, a good correlation between the cusp/cleft and L1 measurements was seen, consistent with directs entry of the magnetosheath plasma into the high latitude magnetosphere during this period of southward IMF.

4. Discussion and Summary

We have used the "frozen-in" ionization state of solar wind Fe ions as a tracer to study the transport of solar plasma material to the cusp/cleft during a CME. The CME/magnetic cloud event of May 1-3, 1998 exhibited a significant enrichment of Fe ions and large variations in the charge state distribution [*Gloeckler et al.*, 1999] that made it particularly suitable for a study of this nature. Observations of the Fe charge state made by ACE at L1, and by POLAR in the cusp/cleft region were compared. During periods of southward IMF a very good correlation between the two measurements was found indicating that both spacecraft were sampling the same CME plasma population. The time scales of these observations were consistent with direct entry of solar wind plasma via a sub-solar field line merging site.

Particles with energies greater than the several keV/e expected from un-accelerated solar wind were observed in the cusp/cleft region during these periods of direct entry. Cusp energetic particles (CEPs) were first reported by Chen et al., 1997 and have been a source of some controversy. Several mechanisms have been proposed to explain the energization including in-situ processes within the cusp [*Chen et al.*, 1998] and bow shock acceleration [*Chang et al.*, 1998]. The low fluxes of Fe ions examined in this study limit the possibility of producing the full particle distributions necessary to address this question. However, the use of these observations to identify periods when Polar is well connected to field lines containing fresh solar wind material, will allow the use of the more common H^+ and He^{++} ion species. This is the subject of a separate study.

The study interval did not provide a good period of stable northward IMF. However, a period of predominantly northward, though disturbed, IMF was observed and from this there was possible evidence for delayed transport that might be expected from solar wind entry away from the sub-solar point, for example as a result of lobe reconnection. The pitch angle distribution during this period was different to those observed for southward IMF. This indicates that a different field configuration or region of the cusp/cleft was being sampled. A detailed examination of the proton pitch angle distributions measured by POLAR (not shown) indicated multiple flow reversals consistent with a complex reconnection pattern. Therefore the observed differences may correspond to a combination of new and old material, the details of which cannot be resolved due to the poor time resolution of the Fe measurements. However, we have demonstrated a powerful tool that can be used for investigating this possible delay in the connectivity of solar wind during northward IMF. Identification and analysis of observations from other periods should help to clarify the situation.

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