The latitude relation between small-scale field-aligned currents and energetic particle precipitation in the low-altitude cusp

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Abstract. We examined some 75 sets of observations from the low altitude Earth orbiting DMSP, Ørsted and CHAMP satellites which were taken in the region of the nominal cusp. It was our objective to determine whether the actually observed cusp locations as suggested by magnetosheath-like particle precipitation ("particle cusp") and intense small-scale field-aligned currents ("current cusp"), respectively, were identical and were further consistent with the statistically expected latitude of the cusp (termed "statistical cusp") as derived by Newell et al. (1989).

The geocentric locations of the satellites were converted into AACGM coordinates, and the geomagnetic latitude of the cusp boundaries (as indicated by precipitating particles and small-scale field-aligned currents) set in relation to the IMF-\textit{B}_z dependent latitude of the equatorward boundary of the statistical cusp.

We find that the actually observed latitude of the particle cusp matches well the statistically expected latitude while the current cusp appears to cover the entire statistical cusp but also an 1\textsuperscript{st} wide section extending beyond the equatorward boundary of the statistical cusp. This leads us to suggest that intense small-scale field-aligned currents are generated in the cusp but also in the transition zone between the low-latitude boundary layer (LLBL) and the cusp, probably within both regimes, the cusp and the open LLBL. The field-aligned currents are possibly a consequence of turbulence and/or instabilities associated with the process of opening previously closed magnetospheric field lines and merging them with the interplanetary magnetic field.

1 Introduction

This paper aims at making a detailed examination of the cusp latitude inferred from two different ionospheric signatures, namely the occurrence of magnetosheath-like particle precipitation and of intense small-scale magnetic field perturbations respective field-aligned currents (FAC).

The average location of the low-altitude cusp was mapped by Newell and Meng (1988) from the analysis of a huge number of spectra of precipitating ions and electrons supposedly originating in the magnetosheath. They used spectrometer data which had been collected by various DMSP satellites over a time span of several years. Identification of the cusp in this manner is based on the assumption that intensity and energy distribution of precipitating particles in the cusp region resemble the magnetosheath plasma population more than in any other region of the magnetosphere (Newell and Meng, 1988). We refer to the cusp identified in this way as the "statistical cusp".

Recently it was discovered that large and highly localised magnetic field perturbations with scale sizes ranging from several hundred metres up to a few kilometres are frequently observed in or near the nominal cusp region (Stauning et al., 2003; Neubert and Christiansen, 2003; Watermann et al., 2004). They are indicative of a locally confined area of high FAC intensity of small spatial scale and map out a region which approximately overlaps the statistical cusp.

Newell et al. (1989) derived a quantitative relation between the magnitude of the IMF-\textit{B}_z component and the most probable equatorward boundary of the statistical cusp. This "statistical cusp equilibrium boundary" defines the reference latitude against which we compare our observations from individual DMSP, Ørsted and CHAMP cusp passes.

The DMSP satellites possess a high-inclination synchronous circular orbit at some 850 km altitude above the ground. The Ørsted satellites moves in a slowly precessing high inclination elliptic orbit with about 620 km and 860 km perigee and apogee, respectively. The CHAMP satellite follows a circular slowly precessing high inclination orbit. At the time we took our measurements, CHAMP was about 425 km above the ground; in general its altitude can change quickly due to increased air drag and lift manoeuvres.

We studied some 75 cases of cusp observation collected from these three satellites during the first SIRCUs campaign,
February 16-22, 2002. SIRCUS is the acronym of a multi-instrument observational program which focusses on a detailed investigation into the properties and dynamics of the low-altitude cusp. More information on SIRCUS activities and objectives were documented by The SIRCUS Science Team (2003).

About one third of the cases examined here were inferred from DMSP-F13, -F14 and -F15 particle spectrometer data (termed "particle cusp"), one third from small-scale magnetic field observations made onboard the Ørsted satellite, and one third from small-scale CHAMP satellite measurements (the latter two are termed "current cusp").

We shall point out that the definitions of "statistical cusp" and "particle cusp" build on the same physical quantities, namely the spectral characteristics of charged particle precipitation. The difference is merely that the term "statistical cusp" refers to the average or statistically expected particle cusp location as defined by Newell and Meng (1988) while the term "particle cusp" refers to an individual satellite pass where the actual cusp location can deviate from the expected one.

2 Space Environment

Solar wind conditions were largely normal during the first SIRCUS campaign interval. According to ACE measurements, the solar wind velocity fluctuated between 350 and 450 km s$^{-1}$ and the density between 5 and 10 H$^+$ cm$^{-3}$. The interplanetary magnetic field (IMF) was moderately strong, and its x, y, and z-components (in GSM coordinates) fluctuated between -7 and +8, -9 and +9, and -5 and +7 nT, respectively. For reference, ACE level-2 solar wind and IMF data of the time interval under consideration were displayed in The SIRCUS Science Team (2003). The geomagnetic field remained relatively quiet during the campaign interval according to observations from the Greenland magnetometer chain.

Although the interplanetary plasma parameters fluctuated only moderately, the variations of the IMF-B$_y$ and -B$_z$ components are expected to result in detectable shifts of the cusp location — in magnetic local time as well as in magnetic latitude — in accordance with established statistical results (Newell and Meng, 1988; Newell et al., 1989; Aparicio et al., 1991). The IMF dependence is taken into account when comparing actually observed and statistically expected cusp locations.

3 Analysis Method

Since we are concerned with cusp observations we consider only daytime satellite passes. The SIRCUS campaign built on coincident satellite and incoherent scatter radar measurements, therefore the geographic area of the observations was constrained by the field-of-view of the EISCAT Incoherent Scatter Radars at Tromsø and on Svalbard and the Sondrestrom (Greenland) Incoherent Scatter Radar. In consequence we restricted our satellite campaign hours to the 07–16 UT interval.

Small-scale magnetic field variations (in the 0.5–25 Hz range) were tagged as being "present" during a northern hemisphere daytime pass of the Ørsted satellite if they exceeded 15 nT amplitude, and otherwise as being "absent". Similarly, small-scale field-aligned currents (1–50 Hz)
inferred from CHAMP magnetometer measurements were
tagged as being "present" if they exceeded 20 $\mu$A m$^{-2}$, and
otherwise as being "absent", see Fig. 2.

For each time interval marked "present" we computed the
expected latitude of the statistical equatorward boundary of
the cusp according to Newell et al. (1989), using smoothed
ACElevel-2 IMF data taken one hour prior to the satellite ob-
servations. A delay of one hour is appropriate given the aver-
age solar wind speed prevailing during the campaign hours.

In the next step, the geocentric latitude, longitude and at-
titude parameters of each satellite trajectory falling into
the campaign hours were converted into AACGM coordinates (a
system grown out of a combination of CGM and PACE co-
oordinates, see Baker and Wing (1989) and Gustafsson et al.
(1992)). The AACGM latitude difference between the ob-
served equatorward boundary of each "$\delta B$ present" respec-
tively "$\vec{j}$ present" interval and the equatorward boundary of
the statistical cusp was then determined. The median value
and mean absolute deviation of these differences over the en-
tire campaign interval were then computed.

The procedure was then repeated with the observed pole-
ward boundaries of "$\delta B$ present" and "$\vec{j}$ present", respec-
tively, and the equatorward boundary of the statistical cusp
in order to compute the difference between the observed
poleward boundary of the current cusp and the equatorward
boundary of the statistical cusp.

The same procedure was applied to the actually observed
and the statistically expected equatorward boundaries of the
particle cusp and to the difference between the actually
observed poleward boundary and the statistically expected
equatorward boundary of the particle cusp. The results from
all of these computations are displayed in Fig. 4.

4 Analysis Results

The comparison between the equatorward and poleward
boundaries of the particle cusp and the current cusp, respec-
tively, on one hand, and the equatorward boundary of the sta-
tistical cusp on the other, rendered the numbers reproduced in
Table 1.

The centre of the particle cusp coincides approximately with
the centre of intense small-scale FAC inferred from
magnetometer observations made by the CHAMP satellite.
The equatorward boundaries of both coincide approximately
with the poleward boundary of intense small-scale magnetic
field perturbations observed by the Ørsted satellite. The parti-
cle cusp and the current cusp inferred from CHAMP appear
to be found slightly poleward of the statistical cusp, but
the difference lies within the statistical uncertainty and is
insignificant. The current cusp inferred from Ørsted appears
to be approximately centered on the equatorward boundary
of the statistical cusp which is consistent with the results of
Stauning et al. (2003).
Our numbers seem to indicate that the current cusp is wider than the particle cusp. But that is not a valid conclusion and not necessarily a physical fact. We have set our thresholds for high intensity (15 nT and 20 µA m⁻², respectively), based on a reasonable but arbitrary distinction between low and high intensity, and we have set threshold numbers before computing the statistics. Increasing the threshold will certainly result in an apparently narrower current cusp, and vice versa.

It is a bit confusing to note that the current cusp inferred from CHAMP magnetometer data fully coincides with the particle cusp inferred from DMSP spectrometers while the current cusp inferred from Ørsted measurements mainly occupies the region equatorward of the former and appears to straddle the statistical cusp equatorward boundary. We do not consider it unlikely that particle cusp and current cusp do not fully overlap since they represent different physical quantities and generation mechanisms. But it is surprising to observe a systematic difference between the current cusp latitudes inferred from CHAMP and from Ørsted magnetic field measurements. The satellite altitude difference cannot account for it since we converted all positioning information into AACGM parameters—and the difference in altitude was only between 200 and 400 km anyway. Such a difference has a negligible effect on the calculation of the geomagnetic coordinates since the magnetic field is almost vertical at these high magnetic latitudes. The puzzle remains unsolved for the time being and awaits further investigations.

5 Conclusions
During the February 2002 SIRCUS campaign, which took place under relatively quiet interplanetary and magnetospheric conditions, nearly coincident measurements of low-energy charged particle precipitation recorded by the DMSP-F13,
Table 1. Differences between mean equatorward and poleward boundaries of the particle cusp and current cusp, respectively, and the equatorward boundary of the statistical cusp

<table>
<thead>
<tr>
<th>Difference</th>
<th>Difference in [°]</th>
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<tbody>
<tr>
<td>Particle cusp equatorward boundary</td>
<td>0.4° ± 1.1°</td>
</tr>
<tr>
<td>Statistical cusp equatorward boundary</td>
<td></td>
</tr>
<tr>
<td>Particle cusp poleward boundary</td>
<td>1.6° ± 1.2°</td>
</tr>
<tr>
<td>Statistical cusp poleward boundary</td>
<td></td>
</tr>
<tr>
<td>Ørsted current cusp equatorward boundary</td>
<td>-1.0° ± 1.2°</td>
</tr>
<tr>
<td>Statistical cusp equatorward boundary</td>
<td></td>
</tr>
<tr>
<td>Ørsted current cusp poleward boundary</td>
<td>0.6° ± 1.7°</td>
</tr>
<tr>
<td>Statistical cusp poleward boundary</td>
<td></td>
</tr>
<tr>
<td>CHAMP current cusp equatorward boundary</td>
<td>0.3° ± 1.3°</td>
</tr>
<tr>
<td>Statistical cusp equatorward boundary</td>
<td></td>
</tr>
<tr>
<td>CHAMP current cusp poleward boundary</td>
<td>2.1° ± 1.4°</td>
</tr>
<tr>
<td>Statistical cusp poleward boundary</td>
<td></td>
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-F14 and -F15 satellites, small-scale (0.5-25 Hz) magnetic field variations measured by the Ørsted satellite and small-scale (1-50 Hz) field-aligned currents inferred from CHAMP magnetometer observations were collected. They were examined with the objective to identify and map the low-altitude cusp in the northern hemisphere. From a small statistical sample consisting of 25 particle spectra, 24 small-scale δB and 28 small-scale J_|| observations we obtained the following results.

Intense small-scale magnetic field variations resp. field-aligned currents (FAC) were observed in the particle cusp but also at its equatorward side. The latter probably represent the poleward section of the low-latitude boundary layer (LLBL). The small-scale FAC are possibly a consequence of turbulence and/or instabilities associated with the process of opening previously closed magnetospheric field lines and merging them with the interplanetary magnetic field. We therefore suggest that intense small-scale FAC are characteristic of the cusp and the open part of the LLBL, i.e., they are not a unique feature of the low-altitude cusp in a strict sense. Since our observations were taken under quiet conditions it seems unlikely that highly variable magnetospheric dynamics have resulted in rapidly changing conditions which could introduce a significant temporal variability to the cusp location. Under very disturbed conditions a direct comparison between data from different satellites would be subject to large uncertainties unless the measurements were taken simultaneously.

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References


