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Auroral Precipitation / Ion Upwelling as a Driver of Neutral Density Enhancement in the Cusp

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Abstract

Soft electron precipitation in collaboration with ion upwelling is investigated as a possible driver of the cusp neutral density enhancement discovered by the CHAMP satellite. A time-dependent, three-fluid numerical model is used to simulate the vertical ionospheric and thermospheric response for this type of event. Particle data from the FAST satellite from a single favorable conjunction alignment event with CHAMP are input to the model. Results are given which suggest that altitude-dependent neutral density enhancements accompany ion upwelling that is driven by soft electron precipitation. The enhancement mechanism is summarized as follows. Sufficiently soft electron precipitation transfers energy to the ambient electron “gas”, which subsequently undergoes a thermal (upward) expansion. This establishes a vertical ambipolar electric field which pulls the ions upward. The momentum carried by up-flowing ions is significant and results show it to be capable of dragging neutral gas upward to create density structures above the F-region.

Keywords: ionosphere, thermosphere, cusp, neutral density, electron precipitation, ion outflow, ion upwelling

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1 1. Introduction

Thermospheric dynamics, including the variability of neutral density, has been studied theoretically and observationally for decades (see Prölss (1997) and references therein). Regions of enhanced neutral densities are of prime concern for the tracking of satellites and space debris. Due to the poor coverage of density details by empirical models, large error margins must be considered when predicting the orbits of these objects. In the case of Low-Earth Orbiting (LEO) satellites, unaccounted for density anomalies cause cumulative along-track errors. For the CHAMP satellite, orbit predictions had to be updated daily to ensure proper pointing of the ground station antenna during down-link. A step forward in predicting density variability at high latitudes came with the modeling of large-scale “neutral density cells” (Crowley et al., 1996) which vary considerably with magnetic activity level and are driven predominantly by large-scale Joule heating. These 2,000 km scale density enhancement and depletion structures were observed in the high-latitude region by satellites orbiting near 250 km altitude and are well-reproduced by general circulation models over a range of K_p values.

Subsequent to this progress, smaller 300 km scale pockets of enhanced density at 400 km altitude near each magnetospheric cusp were reported by Lühr et al. (2004). While some ideas exist in the literature (Schlegel et al., 2005; Clemmons et al., 2008; Crowley et al., 2010), there is no generally accepted explanation for these structures. These cusp enhancements are unique not only because of their smaller scale-size, but also because they are well-correlated with small-scale field-aligned currents (Lühr et al., 2004). In a statistical study Rother et al. (2007) showed that the cusp is the preferred region for intense small-scale field-aligned currents (FACs). In addition, unlike the larger scale enhancements mentioned above, the cusp enhancements are encountered even during quiet conditions (Liu et al., 2005). Due to the complexities of the processes in the cusp region and a lack of good observational data, predictive modeling improvements for this density anomaly have been hampered. Only recently has a model successfully predicted a few density events observed by CHAMP (Crowley et al., 2010) and only for a small sub-class of events (very strong B_y). Predictive modeling for other events has continued to be difficult to attain.

The present work puts forth the case that soft electron precipitation, in association with ion [upwelling](#), ~~outflow~~, may be driving the cusp density enhancements that CHAMP observes. [Soft electron precipitation in the cusp](#)

can produce auroral forms (Eather and Mende, 1971) which have proved useful in observational research of ion upwelling (Moen et al., 2004). ~~Due to the auroral forms associated with this precipitation in the cusp region~~ ~~[[Eather and Mende, 1971]], the term “auroral precipitation” is used as a synonym for soft electron precipitation within the present work.~~ The remainder of the current section gives an overview of the related science in this area, including discussions of Joule heating and **cusp** auroral precipitation as possible drivers of the density enhancement. Section 2 presents data from a favorable conjunction of the CHAMP and FAST satellites used as input to a numeric simulation. Section 3 presents results from a numerical simulation which supports auroral precipitation as a possible driver of the enhancements. Concluding remarks are contained in Section 4.

1.1. Cusp density enhancement

The small-scale density enhancement in the dayside cusp region was first observed with CHAMP’s highly-sensitive accelerometer at about 400 km altitude and reported by Lühr et al. (2004). The satellite detected enhanced neutral densities as it passed over the cusp region where strong field-aligned currents were simultaneously measured. Enhancements were observed in both hemispheres, however they were found to be somewhat less prominent at the southern cusp. Neutral density is calculated from CHAMP’s accelerometer by inverting a standard satellite drag formula. This allows the calculation of mass density (which causes the satellite drag) from the ram-direction drag force (measured by the accelerometer). The sensitivity of the accelerometer allows for mass density resolution down to $6 \times 10^{-14} \text{ kg/m}^3$ (Rentz and Lühr, 2008; Rother et al., 2007).

Lühr et al. (2004) point out that peaks observed by CHAMP are “encountered almost every time when crossing the cusp region” (i.e., where soft precipitation is very common). While the density structures tend to occur in the same general location of the cusp and have similar north-south scale sizes ($350 \pm 150 \text{ km}$), the authors emphasize that the density enhancements are associated with fine-scale currents, having magnitudes the order of $150 \mu\text{A/m}^2$ and kilometer-scale polarity reversals. The enhancement mechanism they propose is described as localized Joule heating associated with small-scale currents, whereby ionospheric currents heat the neutral atmosphere at a lower altitude, say the E-region, and produce upwelling to CHAMP altitude. It should be noted that Prölss (1981) found similar density enhancements in

74 the auroral zone at lower altitudes (~ 250 km) using data from the ESRO 4
 75 satellite and suggested a similar driving mechanism.

76 In addition to that proposed mechanism, there are several others which
 77 may act as drivers of the enhancement in this region (e.g., see Schlegel et al.,
 78 2005). Here we discuss two additional possible mechanisms to provide context
 79 for the present work: large-scale Joule heating and auroral precipitation.

80 1.2. *Joule heating as a possible driver of cusp enhancement*

81 The high-latitude neutral density structures described in Crowley et al.
 82 (1996) were first detected with simulation runs of the NCAR Thermosphere
 83 Ionosphere General Circulation Model (TIGCM) (Roble et al., 1988). As
 84 modeled, these three-dimensional density “cells” extend horizontally 1000–
 85 2000 km and vertically as high as 250–350 km altitude, depending on the
 86 magnetic activity level. Cells can be either enhancement or depletion struc-
 87 tures (relative to the hemispheric average) and are found poleward of about
 88 50 degrees latitude in a system of 2 to 4 cells. This system of cells is
 89 well-reproduced by large-scale general circulation models and appears to be
 90 generated by a combination of Joule heating and momentum forcing effects
 91 (Schoendorf et al., 1996a,b). According Schoendorf et al. (1996b), the cellular
 92 structures begin to “wash out” with increasing altitude over 200 km and are
 93 no longer visible at altitudes above 250 km for quiet conditions and 350 km
 94 for active conditions. This model prediction is inconsistent with CHAMP
 95 observations of regular cusp density enhancements during both active and
 96 quite periods at 400 km.

97 In part to look for evidence of these cellular structures, Liu et al. (2005)
 98 performed a statistical study of all CHAMP observations during 2002. Their
 99 study confirmed the Lühr et al. (2004) report of small-scale density enhance-
 100 ments in the cusp region, but they were unable to identify any large-scale cells
 101 at 400 km altitude for quiet conditions. For moderately active conditions, a
 102 possible 1000 km scale enhancement cell was identified but without a corre-
 103 sponding depletion cell. Depletion cells are predicted to be more prominent
 104 than enhancement cells at higher altitudes. From this evidence, Liu et al.
 105 (2005) found it difficult to link the cellular density structure mechanism to
 106 the cusp enhancements observed by CHAMP.

107 Schlegel et al. (2005) also presented a study of CHAMP cusp observations,
 108 showing results from the 7-day *Satellite and Incoherent Scatter Radar Cusp*
 109 *Studies* (SIRCUS) campaign (Watermann et al., 2005), which coincided with
 110 EISCAT observations. The pattern that emerges from their work is that a

strong density maximum generally occurs around 75° magnetic latitude and ~ 1000 – 1100 MLT, near the location of the cusp. No comparable density enhancements were seen in corresponding simulations using the Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM) (Roble and Ridley, 1994). Based on these results and other considerations, Schlegel et al. (2005) conclude that the density enhancements observed by CHAMP during quiet conditions must not be driven by large-scale global processes. Subsequent to this work, Rentz and Lühr (2008) performed a systematic study of the cusp-related density anomaly based on CHAMP observations of the 4 years 2002–2005. They showed, among other results, associations, a clear correlation dependence of the anomaly’s amplitude with on the solar EUV flux and an even stronger association with dependence on the solar wind merging electric field.

Demars and Schunk (2007) approached the problem using a high-resolution model of the global thermosphere (see Ma and Schunk (1995) for details of the model itself). The model injects ion-neutral frictional heating into the cusp region while allowing for the Earth’s atmosphere to rotate through this generic heating source. Maximum heating is maintained for 2 hours, with a 1 hour ramp-up and ramp-down. The conclusion they reach is that, in order to replicate the CHAMP observations of increased densities by a factor of 1.8 at 400 km altitude, the ion-neutral frictional heating needs to be increased by a factor of 110 over the background, driving the ion temperature up from the nominal 1000 K to more than 10,000 K in the cusp region. While the results they obtain are similar to the CHAMP observations in magnitude and latitudinal profile, the authors emphasize that their goal is only to replicate the CHAMP results by injecting (forcing) heat into a neutral gas and observing the thermospheric response. The authors make no claim as to the specific mechanism responsible for the heating.

Recently, however, Crowley et al. (2010) did succeed in showing that Joule heating, as determined using TIME-GCM driven by high-fidelity high-latitude inputs specified by the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) algorithm, can reproduce the small-scale enhancements observed by CHAMP reasonably well for a high-energy event. This result is from a case study using data from a DMSP satellite that was favorably positioned for the event to provide the high-resolution observations. The model shows a maximum in height-integrated Joule heating of 60 mW/m^2 . The authors conclude that the event resulted from “unexpectedly large amounts of energy” entering the cusp during a period with a strong interplanetary

149 magnetic field, B_y (20 nT).

150 The net result from these studies would seem to indicate that [results from](#)
 151 modeling of the cusp region with large-scale Joule heating and momentum
 152 forcing mechanisms are generally inconsistent with observations by CHAMP
 153 during geomagnetically quiet conditions.

154 1.3. Auroral precipitation as a possible driver of cusp enhancement

155 Based upon observations by the Streak satellite, Clemmons et al. (2008)
 156 also report on the cusp density enhancements but from a lower altitude. In
 157 contrast to observations by CHAMP, the Streak satellite observed very lit-
 158 tle density increase near the southern cusp in the altitude range of 123–325
 159 km. They suggest the following (paraphrased) argument: if Joule heating is
 160 driving an enhancement seen by CHAMP at 400 km, and if that enhance-
 161 ment is being driven from below 200 km, then Streak, between those two
 162 altitudes, should see a larger enhancement in the cusp region than it encoun-
 163 ters. Further, they propose an altitude dependent mechanism to explain this
 164 involving heating due to soft precipitation. Energy from soft electron precip-
 165 itation is [typically](#) deposited at higher altitudes than Joule heating, allowing
 166 observational consistency for the two satellites: if neutrals are upwelling from
 167 an altitude between the two orbits, CHAMP could see an enhancement that
 168 Streak did not. Figure 5 in Clemmons et al. (2008) illustrates this idea with
 169 plots from model results predicting specific energy deposition rates and neu-
 170 tral vertical wind speed for several electron precipitation inputs. Simulation
 171 results were based upon the electron transport model of Strickland et al.
 172 (1993) and the theory of Hays et al. (1973).

173 Clemmons et al. (2008) propose an underlying density enhancement mech-
 174 anism based on energy transfer from soft electrons directly to neutrals. The
 175 present paper agrees with the idea that soft electron precipitation provides
 176 a good explanation for the apparent altitude dependency of the cusp density
 177 enhancement, but proposes an alternative underlying enhancement mecha-
 178 nism, one which relies on processes associated with ion outflow rather than
 179 direct energy transfer to neutrals. We present this new mechanism without
 180 debating the relative merits of the two mechanisms.

181 The processes of ion outflow involve transport of ions from Earth’s high-
 182 latitude ionosphere to the magnetosphere. In the auroral and cusp regions,
 183 these processes can be roughly grouped into two sequential stages: 1) auro-
 184 ral bulk ion upwelling (large initial velocity increase of gravitationally bound

185 ionospheric ions) and 2) ion energization (subsequent acceleration to gravi-
 186 tational escape energies). (See Yau and André (1997); André and Yau (1997)
 187 for a general review.) Two mechanisms have been theorized to drive the first
 188 of these stages: Poynting flux (with Joule dissipation) and soft electron pre-
 189 cipitation (with electron heating / ionization). (See, for example, Strangeway
 190 et al., 2005). For the purposes of the present paper, we focus only on the
 191 soft electron precipitation mechanism within the upwelling stage of the ion
 192 outflow process.

193 A number of reports have described the response of high-latitude ion up-
 194 welling to the inputs of soft electron precipitation. These can be roughly
 195 categorized as studying the phenomenon from the perspective of numerical
 196 simulation (e.g., Whittaker 1977; Su et al. 1999), observation (e.g., Seo et al.
 197 1997; Ogawa et al. 2000; Strangeway et al. 2005), or both (e.g., Liu et al.
 198 1995; Caton et al. 1996). (See also Horwitz and Moore (1997) for a review.)
 199 The papers listed seem to agree on the general mechanisms and response
 200 characteristics, which are summarized as follows, with specific example ci-
 201 tations as appropriate. Sufficiently soft auroral precipitation ($< \sim 500$ eV)
 202 initiates a "strong upward plasma expansion" (Liu et al., 1995) above the
 203 F-region which increases with altitude (e.g., Fig. 2, 3, 7, in Su et al., 1999).
 204 The precipitation quickly transfers energy to the ambient electron "gas" re-
 205 sulting in an electron temperature increase. Whittaker (1977) reports that
 206 this initial increase occurs on a time-scale of about 2 minutes. The electron
 207 temperature increase is substantial (e.g., Fig. 1b, 4b, in Su et al., 1999) and
 208 correlates to both decreasing electron energy and increasing electron energy
 209 flux (e.g., Fig. 4a, 5a, in Seo et al., 1997). The electron gas subsequently
 210 undergoes a thermal (upward) expansion, establishing a vertical ambipolar
 211 field which pulls the ions upwards through the parallel electric field arising
 212 from the need for charge neutrality. Temporally, the ion velocity and ion
 213 flux seem to respond with a sharp increase on a time scale of 10-15 minutes
 214 and then decrease to a somewhat lesser positive steady-state value over the
 215 course of about an hour. (Fig. 7a, 7b, in Su et al., 1999). The net increase
 216 of these two parameters correlates to increased electron temperature (e.g.,
 217 Fig. 1b, 1a, in Seo et al., 1997). Ion temperature also increases rapidly in
 218 the first 10-15 minutes and then levels off to a higher value over the course
 219 of about an hour (Fig. 7d in Su et al., 1999).

220 Due to the topic area involved, the above studies are primarily concerned
 221 with the response of ions to soft electron precipitation. As such, they deal
 222 primarily with plasma populations and ~~not so much~~ minimally with neutrals.

Given that the "strong upward plasma expansion" described above travels within a thermosphere dominated by neutral gas, it is reasonable to assume that an upward expansion of neutrals may also occur. The cusp is a relatively confined small-scale region which often encounters soft electron precipitation and the subsequent ion upwelling. We propose that localized neutral density is increased in this process and this could contribute to the cusp density enhancements observed by CHAMP. This idea is explored in Section 3.

We also note that Alfvén waves, ~~often associated with soft electron precipitation, incident from higher altitudes~~ may promote density increases via localized Joule heating, alone or in combination with the above auroral precipitation mechanism. This particular avenue, however, is not investigated in the present work.

2. Feb 5, 2003 conjunction data

To provide realistic inputs for the numerical simulation and result comparison, we take data from a single event involving two satellites in conjunction near the northern dayside cusp shortly after 16:00 UT on Feb 5, 2003. The CHallenging Minisatellite Payload (CHAMP) (Reigber et al., 2002) provides neutral density, electron density and temperature, and FAC measurements, from an altitude of ~ 400 km. The Fast Auroral SnapshoT (FAST) Explorer (Carlson et al., 1998) provides detailed plasma particle data from an altitude of ~ 2600 km. Satellite traces for the event are shown in Fig. 1 with CHAMP orbit trajectories labeled with asterisks and FAST trajectories with triangles. (Satellite position data was obtained from NASA SSCweb.) In this figure, the trajectories are magnetically mapped via IGRF to a common altitude of 400 km and plotted in magnetic coordinates.

Solar wind (SW) and interplanetary magnetic field (IMF) data taken by the ACE satellite prior to the event were as follows: SW speed = $572(\pm 3.4)$ km/s, SW density = $2.14(\pm 0.11)$ cm $^{-3}$, IMF $B_x = 7.42(\pm 0.23)$ nT, IMF $B_y = -2.71(\pm 0.54)$ nT, IMF $B_z = -1.61(\pm 0.91)$ nT. These data are average values for the 1 hour period 14:20 to 15:20 UT which accounts for a SW travel lag-time of approximately 43 minutes; standard deviation is in parentheses. Vector quantities are represented in the Geocentric Solar Magnetospheric (GSM) coordinate system. Magnetic activity was moderate during the event with $K_p = 4-$ and $AE = 279$.

Observations from CHAMP are shown in Fig. 2. On this day, CHAMP travels northward on the night side, crosses the night-side auroral oval at

15:55 UT, passes over the polar cap, and finally flies southward over the day-side oval in the 14 LT sector. The time of interest for this study is 16:02 to 16:06 UT. In the top panel, we find a distinct peak in neutral density at 16:03 UT (marked with an arrow). This is a common feature for the cusp/cleft region as has been shown in several studies. For this event, the neutral density increase is approximately 16% over the background. In the second and third panels, the electron density exhibits a minimum at that time while the electron temperature peaks here. This is also quite typical common for the cusp/cleft according to Prölss (2006). It also fits the idea of an ion outflow. The two bottom panels show the FACs which were derived from magnetometer measurements assuming perpendicular sheet geometry (Lühr et al., 1996). We find bursts of kilometer-scale FACs (Rother et al., 2007) occurring with the density peak. At the same time, intense large-scale FACs (<150 km) are observed. Positive values denote upward currents.

It is interesting to note that while the neutral density peaks at 16:03 UT and 78.5° MLAT, the small-scale FACs occur slightly equator-ward of the neutral density peak, peaking at 16:03:40 UT and 75.9° MLAT. This difference in latitude is typical for these events and is thought to result from the fact that the plasma providing the current follows the local magnetic field inclination, while the neutral particles are not so constrained. The fine-scale FACs are very similar to data shown by Lühr et al. (2004) and the association of density enhancements with these currents is a principal conclusion of that paper. For this event, electron density, measured with a planar Langmuir probe (Fig. 2, second panel), exhibits a minimum of approximately $2 \times 10^5/\text{cm}^3$ that overlaps (in time and space) with both the density enhancement and the small-scale currents. The electron temperature also reaches a broad peak of ~ 3300 K in this region.

Corresponding FAST data are shown in Fig. 3 in an expanded 2-minute view of the cusp crossing. These data, acquired within 7 minutes of the CHAMP crossing, show plasma and magnetic field measurements in this same region. (Electric field measurements are not available for this event.) The top panel shows kilometer-scale FACs derived from FAST magnetic field data, the second and third panels show electron energies and pitch angles, the fourth and fifth panels show ion energies and ion pitch angles.

The FACs in the first panel were computed by an algorithm similar to that of Lühr et al. (1996) at a sample period of 0.25 s which corresponds to a spatial scale of 1.6 km at FAST's orbital speed of 6.5 km/s. ~~This spatial scale is comparable to the electron inertial length λ_e of 1–2 km for~~

297 ~~densities typically observed at FAST's altitude; field-aligned current sheets~~
 298 ~~thinner than λ_e are unstable (Seyler and Wu, 2001) and are therefore not~~
 299 ~~expected to map to CHAMP altitudes.~~ The left-hand y axis scale for this
 300 panel shows the value at FAST altitude (~ 2600 km) and the right-hand scale
 301 shows the value mapped to CHAMP's altitude (~ 400 km). This factor of
 302 1.55 difference is due to magnetic field convergence between the two altitudes.
 303 Strong **fine-scale** FACs are again observed by FAST with a peak amplitude of
 304 $\sim 22 \mu\text{A}/\text{m}^2$, or $\sim 34 \mu\text{A}/\text{m}^2$ when mapped to CHAMP altitude. This is lower
 305 but comparable to the peak amplitude of $\sim 52 \mu\text{A}/\text{m}^2$ observed by CHAMP
 306 (panel 4 of Fig. 2). **This difference in peak amplitude may be due to spatial**
 307 **or temporal variations along the length and height of the current sheet layer**
 308 **or possibly due to differences in sampling scales of the two satellites.** Aside
 309 from the field-aligned currents, the notable features in these data are the
 310 precipitating electrons at 16:11 UT having energies ranging from thermal to
 311 hundreds of eV and pitch angles that are fairly isotropic except for a loss
 312 cone. This population is typical of precipitation in the cusp region (Pfaff
 313 et al., 1998).

314 We have good reason to believe that both satellites passed through the
 315 cusp for this event. The CHAMP signature of elevated electron tempera-
 316 ture and depressed electron density is associated with cusp crossings (Münch
 317 et al., 1977; Prölss, 2006). FAST particle instruments show clear signatures
 318 with electrons and ions of cusp energies (Newell and Meng, 1988) and rising
 319 ion energies with decreasing latitude (Reiff et al., 1977). A cusp crossing
 320 with similar energies and location with respect to magnetic noon is given
 321 by Farrugia et al. (1998) (see Plate 1 therein). In addition, both satellites
 322 observe small-scale FACs which are common with cusp crossings (Neubert
 323 and Christiansen, 2003).

324 To compare spatial and temporal locations of the two encounters, we
 325 take the peak FAC amplitude observed by both satellites as a possible lon-
 326 gitudinal feature within the cusp. CHAMP encounters peak FAC current at
 327 about 16:03:40 UT, 76.3° ILAT, 13:49 MLT, and FAST at 16:10:50 UT, 75.2°
 328 ILAT, 11:03 MLT. The two ILAT positions are 1 degree apart, close enough
 329 to be considered within the latitudinal extent of the cusp, and both are at
 330 reasonable latitudinal locations for $B_z \cong -1.6$ nT (see Fig. 5a in Newell
 331 et al., 1989). The 2.77 h local time span between the satellites falls within
 332 the typical cusp longitudinal extent of 12 ± 2 hours MLT (e.g., Zaitzeva and
 333 Pudovkin, 1976) and within the statistical width for negative B_z conditions
 334 (2.8 h) presented in Newell et al. (1989). Longitudinal cusp extents can cer-

tainly be wider than these averages as documented, for example, in Maynard et al. (1997). The cusp event from that study was measured at a minimum width of 3.7 h in magnetic local time. This measurement was based upon a single unique pass of the DMSP F11 satellite along the longitudinal extent of the cusp with simultaneous ground-based optical measurements at Svalbard.

A few objective disclosures are in order at this point. For the purposes of the present work, the conjunction described above is intended to provide electron precipitation inputs for a numerical simulation of a cusp neutral enhancement event. The CHAMP satellite provides measurements of the density anomaly being investigated along with other important data. However, its instrumentation suite does not provide the detailed particle measurements required for input to the model. As such, electron precipitation values are taken from the FAST satellite and are considered to be only estimates of the conditions in the vicinity of CHAMP. We make the unavoidable assumption that conditions at CHAMP and FAST are similar enough to provide model inputs. In addition, CHAMP does not have the particle detection capabilities required to definitively confirm passage through the “cusp proper” as defined by Newell and Meng (1988). ~~Therefore, this metric is not available as an indication of cusp transit by CHAMP. Thus one cannot state with conviction either way as to whether CHAMP passed through the cusp. However,~~ Based upon the evidence presented above we contend that it is ~~not~~ ~~un~~reasonable to assume that both satellites passed through the cusp proper and particle precipitation conditions at each satellite were similar enough to justify the estimated values described below.

3. Numerical simulation of neutral enhancement

Here we present details of a numeric simulation which examines underlying physical processes associated with the event described in Section 2. Electron precipitation data from FAST are used as input. Results are compared with observations from CHAMP and FAST.

3.1. Simulation overview and inputs

Simulation results were obtained with a three-fluid (electron, ion, neutral), two-dimensional (x and z) numerical model, the details of which may be found in Zhu et al. (2001). The equation set includes time-dependent terms for the fields and fluid-elements which allows mass acceleration, field perturbations, and waves. In particular, this includes the ion inertial term

which allows for two-fluid wave propagation (i.e., Alfvén waves). Ionization, recombination, and electron heating, based on Lummerzheim (1992), provide support for ionospheric transport processes. The model incorporates detailed electron, ion and neutral dynamics to study various processes (e.g., heating, ion outflow, auroral luminosity) in a general sense.

The relative completeness of this computational code is suitable for the region being studied due to the many important physical processes (thermospheric, ionospheric, magnetospheric) that occur in this small-scale cusp region which may contribute to the observed neutral upwelling. The simulation code is capable of distinguishing between several of the specific sources of heating: large-scale Joule heating of the E-region, electron precipitation, and/or small-scale heating from Alfvén dynamics within FACs. In the current study, however, only electron precipitation is considered. More information about the simulation code and its past applications can be found in Otto et al. (2003).

For the current results, a 800 km (vertical) by 13 km (horizontal) slice of the ionosphere/thermosphere is simulated. The vertical dimension (z) spans altitudes from 100 km to 900 km which includes the region where CHAMP encountered the density enhancement at 400 km altitude. The horizontal dimension (x) is treated homogeneously and does not represent any particular horizontal orientation. For this study the horizontal dimension was restricted in order to examine the vertical transport of the phenomenon.

Eight seconds of FAST data from the ion outflow signature at 16:11 UT were considered for input to the model. Electron precipitation data from this period was filtered such that only data from the loss cone was included. Spacecraft charging and photo-electrons generate a noticeable low-energy contribution, so counts below 30 eV were also removed from consideration. From this subset, the maximum electron energy flux value was found to be 1 mW/m² with an electron characteristic energy value of 175 eV (for a Maxwellian energy spectrum). A scale factor of 2.5 was applied to the energy flux to account for field line convergence between FAST altitude and the simulation region, which resulted in an energy flux increase to 2.5 mW/m². After varying these two parameters in a number of simulation runs, the values of 4 mW/m² and 150 eV were selected for presentation in the current work. This energy flux value is a good bit higher than the scaled value and the characteristic energy is slightly smaller than observed, but these values seemed to provide a better fit with other FAST and CHAMP observations and are similar to those used in other studies (e.g., Liu et al., 1995). The bulk ion

408 velocity at FAST altitude was also calculated for this period and determined
 409 to be upward at ~ 3 km/s. This measurement includes precipitating as well
 410 as upflowing ions.

411 The simulation begins with atmospheric parameters initialized to MSIS
 412 values for a top-side temperature of about 1000 K (Rees, 1989). This tem-
 413 perature was chosen based upon MSIS-E-90 values for the geographic region
 414 where CHAMP encountered the anomaly at 16:05 UT (Hedin, 1991). A
 415 constant electron precipitation using the above values (4 mW/m² electron
 416 characteristic energy value and 150 eV electron energy flux) is injected into
 417 the simulation region for the duration of the run. Atmospheric chemistry
 418 and other parameters are continually adjusted as dictated by the equation
 419 set. Results are given below.

420 3.2. Simulation results

421 Figures 4 and 5 described in this section, show the time evolution of
 422 various parameters for this simulation run. All plots show one-dimensional
 423 profiles of the thermospheric structure (vertical axis, 100 km to 900 km alti-
 424 tude) at the center of the simulation grid ($x=0$) and illustrate the evolution
 425 over a period of 7 minutes. Each line in a plot shows a new temporal snapshot
 426 at approximately 20.5 second intervals. A solid line begins each time series
 427 ($t = 0$ s) with subsequent snapshots continuing with dotted ($t \cong 20.5$ s),
 428 dashed ($t \cong 41$ s), dash-dotted lines ($t \cong 61.5$ s), etc., and then eventually
 429 back to solid lines for the remainder of the series. Note that most plots have
 430 snapshot lines progressing from left-to-right with increasing time, however
 431 the electron temperature (Fig. 4a) and ion velocity (Fig. 5a) have a more
 432 complicated progression.

433 The first set of plots (Fig. 4) shows electron temperature, electron number
 434 density, and electron pressure for 4 mW/m² precipitation energy flux and
 435 characteristic energy of 150 eV. At 400 km altitude, electron temperature
 436 increases to a maximum of about 4500 K but then begins to decrease to
 437 about 3000 K. Electron density triples and electron pressure increases an
 438 order of magnitude, all within the first 1–3 minutes. Similar initial increases
 439 occur throughout the thermosphere except at lower altitudes. While the
 440 vertical profile of density and pressure remain the same general shape, the
 441 rate of increase begins to stratify after this initial surge. Values stabilize to
 442 a maximum value below the F-region peak but they continue to increase at
 443 higher altitudes. This is reflective of the soft electron precipitation depositing
 444 a smaller portion of its energy below the F-region peak.

Ion and neutral response to the inputs are shown in Fig. 5. The first plot shows a very remarkable large ion acceleration, which at 800 km altitude results in a peak upward velocity of 2.35 km/s in only 2.7 minutes. (Average initial acceleration is approximately 15 m/s².) After this peak is reached, the velocity drops somewhat but still remains significant. Lower, at 400 km, the ion velocity rises and stabilizes more quickly to a somewhat modest 500 m/s. (Average initial acceleration is approximately 12 m/s².) Ion motion is the result of the electron pressure increase described above. The expanding electron gas pulls the ions upward through the ambipolar electric field. The upward neutral velocities (Fig. 5b) are much smaller than the ions, as expected, but still reach about 7.5 m/s at altitudes of 425 km and about 22 m/s at higher altitudes. Even though the neutral population greatly out-numbers that of the plasma, the momentum carried by up-flowing ions is significant and capable of dragging neutral gas upward. In this case, the term “drag” should be taken loosely to mean either elastic or inelastic collisions and include, for example, charge exchange which has been discussed by various authors in the past (e.g., Moore, 1980).

The third plot (Fig. 5c) shows the resulting change in neutral density (ratio of time-varying density vs. initial value). Physically, the upward neutral motion shifts the neutral column slightly higher which leads to a moderate density increase, in this case up to 1.3% to 3.5% of the original density in about 7 minutes. Since atmospheric density decreases with altitude on an exponential scale, raising even a small quantity of “dense” neutrals in a vertical column can produce a measurable effect at the higher altitude.

Also of interest is the stratification of the neutral density changes. At 170 km altitude, the density quickly peaks and then stabilizes to an increase of less than 0.5%. Whereas at 400 km and 800 km, two separate regimes of increasing expansion are evident, each at different rates. For the two upper regimes, the evolution has not saturated and the increase in neutral parameters continues to rise at the end of the simulation indicating more room for growth. This stratification above the F-region specifically supports the idea, proposed in Clemmons et al. (2008), that soft electron precipitation can create neutral density structures independent of Joule heating.

Several additional simulations were performed to explore how the parameters varied with different input conditions. The following summarizes some of the trends:

1. The electron precipitation must be sufficiently soft to create the effects

described above. A larger characteristic energy precipitation leads to deposition of the energy deeper in the thermosphere where the neutral inertia is much larger and friction forces prevent the plasma from accelerating efficiently.

2. Larger energy fluxes will considerably shorten the time to reach the same amplitude perturbations.
3. The altitude of the neutral structure depends on the background neutral temperature. A higher initial background temperature raises the density structures in altitude, while a reduced temperature lowers them.

Comparing the above results to values measured by CHAMP (Fig. 2), we find general agreement in electron temperature and electron density. The temperature peak of ~ 3300 K found by CHAMP matches the values at 400 km from Fig. 4a reasonably well, assuming the simulated temperature stabilizes to around 3000 K. The corresponding electron density of $\sim 2 \times 10^5/\text{cm}^3$ also matches reasonably well an assumed asymptote of $\sim 2.2 \times 10^5/\text{cm}^3$ found at 400 km in Fig. 4b. We note, however, that this correlation assumes the location of the CHAMP observed electron temperature peak is conjugate with the ion upwelling signature observed by FAST (where electron precipitation input data was obtained) and that similar conditions existed at both locations. The ending ion velocity of ~ 1.75 km/s at 900 km altitude in Fig. 5a is little over half of the ~ 3 km/s value measured by FAST at 2600 km (see Sec. 3.1). This is a plausible prediction assuming a continued velocity increase over that distance: ion speeds are expected to be higher at 2600 km than at 900 km due to a combination of ion conic folding and continued ion energization (e.g., Miyake et al., 1991).

Comparing relative neutral density increase predictions to CHAMP measurements, however, is much more difficult due to the complicated structure and continued growth. As previously mentioned, parameter values above the F-region have not yet saturated into a steady-state condition and many show a continued increasing rate of change. Electron density and pressure are still increasing, ion velocity has peaked but is decreasing at a small linear rate, and neutral velocity and density both seem to be increasing proportional to time-squared at the end of the simulation. Natural questions to ask at this point are “How long before values settle down?” and “How much does the neutral density increase in that time?” Simple linear extrapolation of the plot values indicate that neutral density at 800 km could increase to about 20% after an additional 10 minutes of “cooking time” (using 1.67 %/min

over 10 minutes). But this is hardly a satisfactory conclusion given the complex interactions within the model. In addition, extrapolation at 400 km is impractical due to the complex structure. Nonetheless, the accelerating neutrals, the increasing neutral density rate and the continued electron density increase suggests that auroral precipitation in conjunction with ion outflow could still be a major driver of the cusp density enhancement. The authors acknowledge this “cooking time” issue is an important problem to be resolved. Continued improvements of the numerical code should clarify this issue over time.

Comparing predictions from this simulation code with the results of Whitteker (1977), Su et al. (1999), and Clemmons et al. (2008), we find some similarities and differences:

1. Simulation runs with the present model showed a very quick increase in electron temperature, on a time-scale of about 1–3 minutes. This trend compares favorably with the results of Whitteker (1977).
2. The present model predicts steady-state electron temperature values which are somewhat lower than those predicted in Su et al. (1999). Simulation runs with comparable input values showed steady-state values which were $1/2$ to $2/3$ of that predicted by Su et al. (1999) (see their Fig. 1b and 4b).
3. For ion velocity, simulation runs with the present model show a quick increase in vertical velocity followed by a slower but sustained decrease. This trend compares favorably with that showed in Fig. 6a and 7a in Su et al. (1999). However, with similar input values, the present model shows a peak which is approximately 50% greater than found by Su et al. (1999), and the peak value is reached in about $1/2$ the time.
4. Using input values of 100 eV and 1.6 mW/m^2 from Fig. 5b in Clemmons et al. (2008), the present model found upward neutral velocities of 8 m/s at 450 km altitude and 18 m/s at 800 km after 7 minutes of simulation time. These values are about $1/4$ to $1/2$ the steady-state values shown in Fig. 5b from Clemmons et al. (2008). Assuming a continued acceleration by neutrals after 7 minutes, upward neutral velocities could reach the values of Clemmons et al. (2008) after a total elapsed time of 15–30 minutes.

It is unclear at this point why simulation results from the model described in the present work differ from the results of Su et al. (1999) as described in points 2 and 3 above. A more detailed comparison of the internal mechanisms

of the two approaches could reveal the cause of this discrepancy. This area, however, is beyond the scope of the present work.

4. Conclusions

The premise that large-scale Joule heating drives the cusp density enhancements observed by the CHAMP satellite has been called into question by several studies (e.g., Liu et al., 2005; Schlegel et al., 2005). Density structures generated at lower altitudes by Joule heating (e.g., Crowley et al., 1996) do not seem to extend upward to CHAMP's altitude of 400 km at least during periods of quiet to moderate magnetic activity. Soft electron precipitation has been suggested as another possible driver of the cusp enhancement at 400 km (e.g., Schlegel et al., 2005). Clemmons et al. (2008) explored this mechanism and showed plausible altitude-dependent density effects based upon precipitation energy deposition arguments which do not rely on large-scale Joule heating. Model results from that study are presented in terms of energy deposition rates and upward neutral velocity as a function of altitude and electron precipitation parameters with the assumption that electron energy is deposited directly to neutrals.

Soft electron precipitation has also been studied in the context of ion outflow with studies presenting strong vertical ion upwelling as a function of altitude and electron precipitation parameters (e.g., Su et al., 1999). The present work proposes that soft electron precipitation in collaboration with ion upwelling can also produce altitude-dependent neutral density enhancements, and may contribute to the enhancement observed by CHAMP.

Numerical simulation results in the present work show a clear multi-step sequence of events producing suitable height stratified neutral density structures initiated by auroral precipitation. This sequence is summarized below:

1. Soft electron precipitation quickly heats ambient electron gas within a fraction of a minute (Fig. 4a).
2. Heated electron gas expands upwards, stabilizing at lower altitudes but expanding above the F-region due to continued precipitation (Fig. 4b and 4c).
3. Ions are drawn upwards due to charge imbalance (Fig. 5a). Maximum vertical velocity is obtained after about 4 minutes at most altitudes and begins to stabilize.

590 4. Neutrals are dragged upwards at a modest pace but continue to accel-
 591 erate past the simulation run. (Fig. 5b and 5c). Small neutral contri-
 592 butions from a lower altitude produce a noticeable density increase at
 593 a higher altitude.

594 The first three steps above have been described by other papers, for example
 595 in the survey by Horwitz and Moore (1997). The current simulation results
 596 show the additional effect on neutral velocity and density enhancement (small
 597 but potentially significant). These results also show this effect is possible
 598 without neutral upwelling from lower altitudes (i.e., large scale Joule heating
 599 in the E-region). Estimates for electron precipitation inputs were determined
 600 from a conjunction of the CHAMP and FAST satellite over the cusp.

601 An important issue yet to be resolved involves how much time is required
 602 for the neutral density to reach a steady-state value and how much density
 603 increase is produced by this mechanism. Further research is needed in this
 604 area.

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Figure 1: CHAMP/FAST satellite track on Feb 5, 2003 in magnetic coordinates: asterisks for CHAMP, triangles for FAST. Coordinate grid shows magnetic local time (MLT) with noon up and magnetic latitude (MLAT) at 400 km altitude (CHAMP’s altitude). FAST trajectory is magnetically mapped via IGRF from 2600 km altitude to CHAMP’s altitude. CHAMP crosses the cusp at about about 16:03:40 UT, 76° MLAT, 13:49 MLT, and FAST at 16:10:50 UT, 75° MLAT, 11:03 MLT.

Figure 2: CHAMP data on Feb 5, 2003, showing (top to bottom) neutral density, electron density, electron temperature, kilometer-scale FACs, and 150 km-scale FAC's. Conjunction alignment feature is taken to be FAC maximum amplitude at 16:03:40 UT, near location of electron density minimum and electron temperature peak. Cusp neutral density peak at about 16:03 UT (marked with an arrow) is slightly poleward of FAC peak.

Figure 3: Two minutes of FAST data from 16:10 to 16:12 UT on Feb 5, 2003, showing (top to bottom) 1.6 km-scale FACs followed by distributions of electron energy, electron pitch angle, ion energy, and ion pitch angle. Conjunction alignment feature with CHAMP is taken to be between FAC maximum amplitude peaks at 16:10:50 UT. Electron precipitation data for model input was taken from ion-outflow signature at about 16:11:20 UT.

Figure 4: Model results showing electron parameters vs. altitude at 4 mW/m^2 precipitation energy flux and 150 eV characteristic energy, left to right: a) electron temperature in 1000 K units, b) electron number density in cm^{-3} , and c) electron pressure in nPa. Plots show time evolution for first 7 minutes of simulation time with each line graphing a new temporal snapshot at 20.5 s intervals. At 400 km, electron temperature evolves from about 1100 K to 4500 K within a minute and then begins to stabilize near 3000 K. Electron density and pressure plots evolve steadily from left-to right.

Figure 5: Model results showing ion and neutral parameters vs. altitude at 4 mW/m^2 precipitation energy flux and 150 eV characteristic energy, left to right: a) ion vertical velocity in m/s, b) neutral vertical velocity in m/s, and c) ratio of changing neutral density to initial values. As in Fig. 4, plots show 7 minutes of time evolution at 20.5 s intervals. At 800 km, ion vertical velocity evolves from to 2.35 km/s in about 2.7 minutes and then begins to lower velocities. At 100–300 km neutral upward velocity and relative density change stabilize quickly, but at higher altitudes continue to increase proportional to time-squared.