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1 Neutral density depletions associated with equatorial
2 plasma bubbles as observed by the CHAMP satellite

3 Jaeheung Park^{a,b}, Hermann Lühr^a, Kyoung Wook Min^b

4 ^a*Helmholtz Center Potsdam (GFZ), German Research Center for Geosciences,*
5 *Telegrafenberg, D-14473 Potsdam, Germany.*

6 ^b*Department of Physics, Korea Advanced Institute of Science and Technology (KAIST),*
7 *373-1 Kuseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea.*

8 **Abstract**

Using CHAMP observations from 2002-2005 we investigate neutral density depletions (NDDs) associated with equatorial plasma bubbles (EPBs). The seasonal-longitudinal distribution of NDDs generally follows that of EPBs. However, there are several important differences between them. The maximum NDD occurrence rate is much smaller than the maximum EPB occurrence. NDDs occur at latitudes north and south of the dip equator with an offset of about 15° , which is collocated with the Appleton anomaly peaks and slightly poleward of EPB occurrence maxima. The NDD occurrence maximizes around 21 LT, and has nearly died out after 23 LT. Meanwhile, the EPB occurrence shows a broad maximum between 20-24 LT. **NDD distribution deviates slightly from that of EPBs shifted toward the region of high ion-neutral interaction. Based on our statistical results, as well as on some physics-based calculations, we suggest that an enhanced friction between ions and neutrals is needed for the NDD generation.**

9 *Key words:* Ionospheric irregularities, Equatorial ionosphere,

Email address: park@gfz-potsdam.de (Jaeheung Park)

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11 **1. Introduction**

12 Neutral density depletions (NDDs) at low magnetic latitudes were first
 13 observed in 1988 by the micro-accelerometer onboard the San Marco V satel-
 14 lite. *Illés-Almár et al.* (1998) showed that NDDs were encountered around
 15 local nighttime (17-03 LT) with scale sizes of 100-200 km, which corresponds
 16 to that of equatorial plasma bubbles (EPBs). They argued that the plasma
 17 density depletion and vertical drift inside EPBs can generate NDDs through
 18 ion neutral collisions. Using the San Marco V data *Bencze et al.* (2000)
 19 gave a more extensive NDD statistics for altitudes below 350 km from April
 20 to December 1988: (1) the local time dependence shows one pre-midnight
 21 and one post-midnight maximum, (2) the seasonal occurrence is higher in
 22 August-December than in May-July, (3) the longitudinal distribution has a
 23 narrow maximum in 30°-60° and a broad one in 90°-240°, (4) the altitudinal
 24 occurrence maximizes around 300 km, and (5) most NDDs have depletions
 25 less than 10% of the ambient mass density. In addition to those indirect
 26 evidences of NDD-EPB relationship, *Bencze et al.* (2000) gave three best
 27 examples which directly show that NDDs are collocated with EPBs. They
 28 also solved the neutral continuity equation including the ion-neutral collision
 29 term under the existence of a vertically drifting EPB. The result could pro-
 30 duce NDDs of about 10% depletion, corroborating that EPBs are the origin
 31 of NDDs. *Schunk and Demars* (2003) simulated EPB-related neutral density
 32 perturbations using a time-dependent 3D thermosphere circulation model.
 33 Their simulation results showed that the neutral density and temperature

inside EPBs could be both depleted and enhanced according to the background conditions. It was suggested that group effects of multiple EPBs can complicate their interaction with neutral wind, which occasionally results in neutral density enhancement within EPBs. The perturbation strengths were about 2-6% in density and 35 K in temperature. They interpreted the neutral perturbations as a result of the interaction between zonal neutral wind and EPBs.

Though *Illés-Almár et al.* (1998) and *Bencze et al.* (2000) were quite pioneering and provided some NDD statistics, several points still remain to be addressed. First, due to unknown wavy structures superimposed on the San Marco V accelerometer data, the NDD statistics was restricted to the bottomside F-region (lower than 350 km altitude). Second, the mission lifetime of San Marco V was only from April to December 1988. Hence, seasonal variation of NDD occurrence rate was given in a restricted form, and the solar-cycle effect could not be investigated. Moreover, due to the short lifetime, the longitudinal NDD distribution could not be considered separately for the seasons. Third, the San Marco V satellite, which had an orbit inclination angle of only 3° , was not able to cover the full latitudinal NDD distribution. Fourth, though San Marco V measured plasma density, the NDD distribution was not studied in relation with the ambient plasma density or EPB depth.

In this paper we use the Accelerometer, Planar Langmuir Probe, and Flux Gate Magnetometer data onboard the Challenging Mini-satellite Payload (CHAMP) satellite for the years 2002-2005 to address the four open issues stated above. In Section 2 we will briefly describe the instruments and NDD

59 detection method. In Section 3 the dependences of NDD occurrence on
60 various parameters, such as season, longitude, latitude, or solar cycle, will
61 be given. The results are interpreted and discussed in Section 4. Finally, a
62 summary is given in Section 5.

63 2. Observation

64 CHAMP was launched on 15 July 2000. As the orbit inclination angle
65 was 87.3° (near-polar orbit), the satellite sweeps all local time sectors every
66 131 days. The altitude was about 450 km right after the launch, and slowly
67 decreased afterwards to reach about 350 km at the end of 2005. CHAMP
68 has an electrostatic accelerometer which measures the non-gravitational ac-
69 celeration precisely (*Lühr et al.*, 2004; *Liu et al.*, 2007). Neutral mass density
70 with the time rate of 10 second is calculated from the accelerometer data.
71 The obtained neutral density reading has a resolution of $2 \times 10^{-14} \text{kg/m}^3$ at
72 10 s sampling. A Planar Langmuir Probe (PLP) onboard CHAMP mea-
73 sures the plasma density every 15 seconds (*McNamara et al.*, 2007). A Flux
74 Gate Magnetometer (FGM) and an Overhauser Magnetometer measure the
75 geomagnetic field. **After preprocessing the geomagnetic field data**
76 **are available** at a time rate of 1 second (*Lühr et al.*, 2003). After **the**
77 **geomagnetic contributions from the Earth’s core, crust, and mag-**
78 **netosphere (hereafter called ‘mean field’) are subtracted** from the
79 **B-field vector, the residual B-field strength (or equivalently the**
80 **component parallel to the mean field)** reflects ionospheric plasma den-
81 sity structures (*Lühr et al.*, 2003; *Stolle et al.*, 2006). In this study we will
82 only deal with the residual **B-field**. As a mean field model the Pots-

dam Magnetic Model of the Earth 4 (POMME4) is used (<http://www.gfz-potsdam.de/magmodels/POMME4>).

Figure 1 gives an example of a typical CHAMP pass in the early night sector. Panel (a) shows neutral mass density variations, and the plasma density measured by PLP is given in panel (b). The residual magnetic field parallel to the mean field is shown in panel (c). Two rectangular boxes mark NDD events. We can see clear depletions of neutral mass density in panel (a), each of which is accompanied by an EPB having similar morphology (panel b). The residual magnetic field given in panel (c) is enhanced within EPBs. Stolle et al. [2006] suggested that the magnetic field strength is enhanced within EPBs to compensate the plasma pressure decrease. NDD depths are around 2-3% while the EPBs show more than 90% depletions of the ambient plasma density. To detect such NDDs related with EPBs automatically, we set up the following procedure. From our selection, daytime (0500 LT-1900 LT), high latitudes (geomagnetic latitude $> 35^\circ$), or active periods ($K_p > 3^+$) are excluded. If an orbit contains unreasonable density values or missing data points, it is omitted, too. Neutral mass density data are first high-pass filtered with a Savitzky-Golay filter (order 3, window size=50 s), and then rectified. The filtered/rectified signal of neutral density is given in panel (d). If the filtered/rectified neutral density exceeds $2.5 \times 10^{-14} \text{ kg/m}^3$ (upper horizontal line in panel (d)), it is considered as an NDD. One NDD should be surrounded by calm background, which corresponds to fluctuations less than $1.5 \times 10^{-14} \text{ kg/m}^3$ (lower horizontal line in panel (d)), for at least 20 seconds. By this criterion, adjacent NDDs can be combined into one event if their spatial separation is small. Then, the residual B-field component

108 parallel to the mean field is high-pass filtered ($T_c = 30$ s) and rectified, as
 109 shown in panel (e). In a way similar to that of *Stolle et al.* (2006) we search
 110 for EPB-associated magnetic fluctuations using a threshold of 0.2 nT (shown
 111 as a thin horizontal line in panel (e)). If there is no EPB-associated magnetic
 112 fluctuation within $\pm 2^\circ$ around an NDD, the neutral density event is omitted.
 113 Also, if the filtered/rectified neutral wind velocity (by a 110 s-window high-
 114 pass median filter) is faster than 60 m/s within an interval of ± 30 s around an
 115 NDD, its neutral density fluctuation is considered questionable and omitted.
 116 In the following sections we will investigate NDDs which have passed the
 117 tests described above.

118 3. Results

119 For the interpretation of the results we have divided the data into three
 120 seasonal bins. Solstitial seasons are defined as 131 days around the two
 121 solstice dates, and the equinoctial season is 66 days around March and 65 days
 122 around September equinoxes: the equinoctial and solstitial seasons overlap
 123 slightly. The seasonal bin size of 131 days was chosen in order to ensure
 124 a full local time coverage. Within the time period from 2002 to 2005 we
 125 have identified 131 NDD events in total. Among them 76 events occurred in
 126 equinoxes, 3 during June solstice, and 80 in December solstice (note that
 127 December solstice and equinox bins share 28 NDD events in common). From
 128 the detected NDDs 103 events occurred in 2002, 27 in 2003, 0 in 2004 and
 129 1 in 2005. In Figure 2(a)-(c) the seasonal/longitudinal (S/L) distributions
 130 of the NDD-to-EPB ratio are given. The NDD-to-EPB ratio is defined as
 131 the ratio between the numbers of NDD and EPB encounters in each cell. As

132 CHAMP sweeps all local times within a seasonal bin, the seasonal dependence
 133 is decoupled from the local time variation. During equinoxes NDDs occur
 134 (i.e. NDD-to-EPB ratio is non-zero) at almost all longitude sectors except
 135 around 180° ; at June solstice the NDD occurrence is quite rare (only three
 136 events in total); around December solstice NDDs occur around the Atlantic
 137 and Indian ocean. The NDD locations run parallel to the dip equator with
 138 a latitudinal offset of about 15° . This trend is corroborated in Figure 2(d),
 139 where the NDD-to-EPB ratio is given as a function of geomagnetic latitude
 140 and local time. We can see that NDD-to-EPB ratio is highest in the window
 141 of 15° - 20° geomagnetic latitude and 20-22 LT. Events are practically absent
 142 in the post-midnight sector.

143 Figure 3(a) gives the number of NDD detections per day in 2002-2005.
 144 Panel (b) represents nighttime (19-06 LT) plasma density averages between
 145 $\pm 35^\circ$ geomagnetic latitudes. Gaps in the curves signify that appropriate PLP
 146 data are missing on that day. Sawtooth-shaped density variations are due
 147 to the CHAMP orbit precession through local time, whose period is about
 148 131 days (slightly longer than 4 months). High plasma densities around the
 149 sawtooth peaks correspond to 19 LT, and low, non-zero plasma densities
 150 are found at about 05 LT. In 2002 and 2003 NDDs are observed generally
 151 when the ambient plasma density is high (i.e. when the CHAMP orbit scans
 152 the early night sectors). Further, the occurrence near June solstice is quite
 153 suppressed even when the CHAMP orbit is located in the post-sunset (~ 19
 154 LT) sector. Panel (c) gives the longitudinal average of the nighttime neutral
 155 density (normalized to 400 km altitude) within $\pm 35^\circ$ geomagnetic latitude.
 156 In panel (d) the solar flux index, $F_{10.7}$, is plotted. It is seen that many NDDs

157 occurred in 2002 when the solar activity is high, but the occurrence was
 158 reduced already significantly in 2003. From 2004 to 2005, when the solar
 159 minimum is approached, the NDD occurrence is rare and sporadic (only 1
 160 event in total).

161 4. Discussions

162 *Illés-Almár et al.* (1998) and *Bencze et al.* (2000) suggested that NDDs,
 163 which were observed below 350 km altitude by the San Marco V satellite,
 164 originate from EPBs. Here we investigate NDDs at the topside ionosphere
 165 above 350 km. Note that we only consider NDDs associated with EPBs,
 166 which is based on the consensus that EPBs generate NDDs (*Illés-Almár et*
 167 *al.*, 1998; *Bencze et al.*, 2000; *Schunk and Demars*, 2003). First, in Figures
 168 2(a)-(c) NDDs appear (i.e. NDD-to-EPB ratio is non-zero) in longitude
 169 sectors where previous studies found seasonal occurrence peaks of EPBs (e.g.
 170 *Kil and Heelis*, 1998; *Huang et al.*, 2001; *Burke et al.*, 2004; *J. Park et al.*,
 171 2005; *Stolle et al.*, 2006). In general, the NDD-to-EPB ratio is not higher than
 172 30%. Some bins around the Indian Ocean, showing the ratio higher than 30%
 173 (dark red), should be interpreted with caution because they contain small
 174 numbers of EPBs (less than 10 in 2002-2005). However, we cannot rule out
 175 the possibility that such high ratio is related with high ion/neutral densities
 176 around the Indian Ocean at 14-18 LT (see Figure 1 of *Liu et al.* (2009)). If
 177 the high ion/neutral densities persist after sunset the ion-neutral interaction
 178 required for NDD generation (*Bencze et al.*, 2000) is increased. Second, the
 179 NDD occurrence shown in Figure 3 is suppressed during low solar activity
 180 periods just as EPB occurrence is. These two results, i.e. consistent S/L

181 distributions and solar-activity dependences of NDDs and EPBs, might be a
182 natural consequence of our NDD selection method: NDDs not accompanied
183 by EPBs have automatically been neglected.

184 However, Figure 2(d) reveals a notable local-time difference between the
185 NDD and EPB distributions. The NDD-to-EPB ratio is maximal around 21
186 LT and nearly zero after 23 LT. Using magnetic field data obtained by the
187 CHAMP/FGM, *Stolle et al.* (2006) found that the EPB occurrence rates in
188 the 20-22 LT and 22-24 LT sectors are comparable, and that there exists a
189 non-negligible EPB activity even after 24 LT. The difference between NDD
190 and EPB distributions can be explained as follows. According to *Illés-Almár*
191 *et al.* (1998) ambient conditions required for generating NDDs are, in addi-
192 tion to the existence of EPBs, a high collision frequency and a large velocity
193 difference between ions and neutrals. We know that the ambient plasma den-
194 sity slowly decreases with local time after sunset, as can be seen in Figure
195 3(b). Therefore, NDDs are expected to occur in the evening shortly after
196 sunset. However, EPBs initiated right after sunset need a time to grow up
197 to CHAMP altitude. They generally encounter CHAMP after 1930 LT (see
198 Figure 8 in *Stolle et al.* (2006)). The maximum NDD occurrence around
199 21 LT in Figure 2(d) is regarded as a trade-off between the existence of
200 EPBs (after 1930 LT) and high collision frequency between ambient ions and
201 neutrals (at early night). Our Figure 2(d) is slightly different from the local
202 time distribution of NDDs in *Bencze et al.* (2000) for altitudes below 350 km.
203 They reported about a premidnight (18-21 LT) and a postmidnight (00-04
204 LT) peak. We cannot confirm the postmidnight NDD occurrence. How-
205 ever, according to *Kil and Heelis* (1998), EPBs below 300 km altitude have

206 a rather symmetric local time distribution in pre- and post-midnight sectors
 207 (see their Figure 4). On the other hand, EPBs above 350 km mainly occurred
 208 before midnight. Such altitude dependence of EPBs might explain the dif-
 209 ference between our results and that of *Bencze et al.* (2000). Post-midnight
 210 NDDs of *Bencze et al.* (2000) could have resulted from the generation of
 211 post-midnight bottomside EPBs by gravity waves. Though the main driver
 212 of gravity waves is the solar terminator (e.g. *Bořka et al.* (2003) and *Altadill*
 213 *et al.* (2004)), there exists non-negligible wave activity in the post-midnight
 214 neutral density (*Liu et al.*, 2009). EPBs generated by post-midnight gravity
 215 waves are, due to the absence of PRE in this local time sector, expected to be
 216 weakly depleted and confined within the bottomside ionosphere. Hence, they
 217 might be observed only by the satellites below CHAMP altitude (*P. Bencze*,
 218 *personal communication*, 2009). In Figure 2 we can see that the NDD occur-
 219 rence peaks around 15° geomagnetic latitude. The latitudinal distribution
 220 of NDDs has not been reported before. *Liu et al.* (2005) showed that the
 221 Appleton anomaly peaks were observed by CHAMP around 15° geomagnetic
 222 latitude in the premidnight sector. According to *Stolle et al.* (2006), EPBs
 223 encountered by CHAMP are distributed around 10° geomagnetic latitude:
 224 they generally occur between the two Appleton anomaly peaks. We may
 225 state that the observed NDDs occur around the Appleton anomaly peaks
 226 rather than around the EPB occurrence peaks. At the Appleton anomaly
 227 peaks the neutral temperature (*Raghavarao et al.*, 1991) is higher, and neu-
 228 tral density (see Fig. 2 in *Liu et al.* (2005)) is not smaller than around the
 229 dip equator, respectively. According to Eq. (5) the ion-neutral collision fre-
 230 quency also becomes larger at the Appleton peaks than at the equatorial

231 region. Hence, the NDD occurrence peaks around the crests of the Appleton
232 anomaly are consistent with the notion that ion-neutral collision plays an
233 important role for NDD generation.

234 The near absence of NDDs around June solstice (see Figure 2) is also
235 consistent with the above argument. The ambient plasma density at equato-
236 rial and low-latitude region reaches its annual minimum during June solstice
237 [*Kil et al.* (2006) and references therein]. The thermospheric neutral density
238 also attains its minimum around June solstice (see *Müller et al.* (2009), *Qian*
239 *et al.* (2009) and references therein). This dependence of NDD occurrence
240 on plasma and neutral density is also quite evident in Figure 3. Although
241 CHAMP passed the post-sunset sector in July 2002, only a few NDDs were
242 detected. Around that month both ambient densities are strongly depleted.
243 The evening prereversal enhancement (PRE), which is also a key factor in
244 causing EPBs, shows a globally averaged minimum in upward drift speed
245 during June solstice, too (*Stolle et al.*, 2008). All these factors combined
246 together result in the NDD suppression during June solstice.

247 The solar activity dependence of NDD occurrence can be interpreted in
248 a similar context. From CHAMP/FGM observations *Stolle et al.* (2006)
249 showed that EPB occurrence rate decreases linearly with the declining solar
250 activity. Similar results were obtained using DMSP satellites at 840 km
251 altitude (*Huang et al.*, 2002). However, NDD occurrence shown in Figure
252 3 changes more drastically between 2002 and 2003. There are 103 events
253 in 2002, but only 27 events occurred in 2003, and almost no events in 2004
254 and 2005. This result again suggests that not only EPBs (their occurrence
255 rate decreases linearly) but also ion/neutral densities and vertical plasma

drift (they also decrease with declining solar cycle) are important for NDD generation. *Stolle et al.* (2006) calculated the fractional number of EPB orbits to that of all CHAMP orbits in a given longitude sector. The maximum value reached up to 80% in the Atlantic sector during December solstice. Similarly, we calculated the fractional number of NDD orbits to that of all CHAMP orbits in a given longitude sector (not shown). Even in the optimal sector it does not exceed 7%, which is much smaller than the EPB occurrence rates observed by CHAMP (*Stolle et al.*, 2006). The small NDD occurrence rate implies either (1) that not all the EPBs are accompanied by NDDs, i.e. some ambient parameters such as ion-neutral collision frequency and relative drift velocity have significant control on NDD generation, or (2) that most of the NDDs exhibit depletions that are below our detection threshold. Currently, we cannot tell which one of them has the larger influence. More precise measurements of plasma and neutral densities are needed to answer the question.

Recently *Park et al.* (2008) had investigated the ratio between plasma and magnetic pressure changes across ionospheric irregularity events. They found that magnetic pressure changes were generally larger than the plasma pressure changes across EPB walls. Therefore, it would be interesting to investigate whether the neutral pressure change associated with NDDs can contribute to the total pressure balance across EPB walls. **In the neutral wind frame the ion motion within the collision-dominated EPB (e.g. *Chakrabarti and Lakhina (2003)*) is described by:**

$$0 = \mathbf{j} \times \mathbf{B} + k_B(T_e + T_i)\nabla n_i - n_i m_i \nu_{in} \mathbf{v}_i \quad (1)$$

279 where n_i is ion number density, m_i ion mass, $\mathbf{v}_i$ ion drift velocity,
 280 $\mathbf{j}$ pressure gradient current density, $\mathbf{B}$ ambient magnetic field, T_e
 281 electron temperature, T_i ion temperature, k_B Boltzmann constant,
 282 and ν_{in} ion-neutral collision frequency. Here we neglected the effect
 283 of gravity and electron-neutral collisions. T_e and T_i are assumed to
 284 be constant. Similarly, the neutral momentum balance equation in
 285 the thermosphere is:

$$0 = k_B T_n \nabla n_n + n_i m_i \nu_{in} \mathbf{v}_i \quad (2)$$

286 where n_n is neutral number density, and T_n the constant neutral tem-
 287 perature. The first two terms on the rightside of Eq. (1) are
 288 proportional to the plasma density gradient. As the third term
 289 depends on the first two terms, it is non-vanishing only within the
 290 thin region of steep density gradient at the EPB/ambient boundary
 291 (hereafter termed ‘frictional transfer region’). Then, integration of
 292 Eqs. (1) and (2) across the EPB wall yields pressure balance equa-
 293 tions for ions and neutrals, respectively:

$$0 = \mathbf{J} \times \mathbf{B} \cdot \hat{\mathbf{r}} + k_B (T_e + T_i) \Delta n_i - \int_0^d n_i m_i \nu_{in} \mathbf{v}_i \cdot d\mathbf{r} \quad (3)$$

$$0 = k_B T_n \Delta n_n + \int_0^d n_i m_i \nu_{in} \mathbf{v}_i \cdot d\mathbf{r} \quad (4)$$

294 where $\mathbf{J}$ is the sheet current density, and d the thickness of the frictional
 295 transfer region. It is clear from Eq. (4) that an NDD, i.e. a neutral pressure
 296 difference across an EPB boundary (the first term on the right-hand side), is
 297 just a consequence of the momentum obtained from the ions at the frictional

transfer region (the second term on the right-hand side). Eq. (4) also shows why ion-neutral collision should be active for NDD generation. By combining Eqs. (3) and (4) we get the total pressure balance equation:

$$0 = \mathbf{J} \times \mathbf{B} \cdot \hat{\mathbf{r}} + k_B(T_e + T_i)\Delta n_i + k_B T_n \Delta n_n \equiv \Delta P_m + \Delta P_p + \Delta P_n. \quad (5)$$

The third term, ΔP_n , is the neutral particle pressure change across the EPB wall. As the neutral atmospheric particles are mostly oxygen atoms at CHAMP altitude (~ 400 km), the neutral number density can be calculated from the mass density measured by CHAMP. We assume 800 K for T_n . Similarly, the second term in Eq. (5) is the plasma pressure difference. Unfortunately, the CHAMP/PLP does not provide reliable ion and electron temperatures. Here, we assume $T_e = T_i = 800$ K because ion and electron temperatures approach thermal equilibrium after sunset in the ionospheric F-region (*Farley, 1967*). The magnetic pressure change, the first term in Eq. (5), can be calculated according to (*Lühr et al., 2003*):

$$\Delta P_m = \frac{\Delta B |B|}{\mu_0} \quad (6)$$

where ΔB is the magnetic field enhancement inside EPBs, $|B|$ the ambient magnetic flux density, and μ_0 the permeability of free space. For the EPB in the left box of Figure 1, we calculate the pressure changes using equations (5) and (6). The ambient plasma density is $5.0 \times 10^6 \text{ cm}^{-3}$, the plasma density inside the EPB is $2.8 \times 10^5 \text{ cm}^{-3}$, and the resultant plasma pressure difference -100 nPa. The ambient neutral mass density is $7.2 \times 10^{-12} \text{ kg/m}^3$, the neutral mass density inside the NDD is $7.0 \times 10^{-12} \text{ kg/m}^3$, and the resultant neutral pressure difference is -79 nPa. ΔB is 6.3 nT, $|B|=37300$ nT,

319 and the resultant magnetic pressure difference 190 nPa. It is clearly seen
 320 that the neutral pressure difference of the NDD approximately compensates
 321 the imbalance between **magnetic pressure** and plasma pressure. For the
 322 EPB in the right box of Figure 1, the same calculation was conducted. The
 323 ambient plasma density is $3.5 \times 10^6 \text{ cm}^{-3}$, inside EPB $5.5 \times 10^5 \text{ cm}^{-3}$, and
 324 the resultant plasma pressure difference -65 nPa. The ambient neutral mass
 325 density is $7.6 \times 10^{-12} \text{ kg/m}^3$, inside NDD $7.5 \times 10^{-12} \text{ kg/m}^3$, and the resul-
 326 tant neutral pressure difference is -55 nPa. ΔB is 4.8 nT, $|B|=33600 \text{ nT}$, and
 327 the resultant magnetic pressure difference 130 nPa. Again, pressure balance
 328 is reached between magnetic and particle (neutral+plasma) pressures.

329 We may use Eq. (4) to get more information about the interaction of ions
 330 and neutrals around EPBs. To solve the integral in Eq. (4) we have to make
 331 a number of assumptions. By assuming that the ion-neutral interaction at
 332 CHAMP altitude (400 km) mainly takes place between the oxygen ions and
 333 atoms, the collision frequency is (*Schunk and Nagy, 2000*):

$$\nu_{in} \approx 4.45 \times 10^{-17} n_n \sqrt{T_i} \text{ (s}^{-1}\text{)} \quad (7)$$

334 Furthermore, we assume that **v_i within the frictional transfer**
 335 **region is constant and perpendicular to the EPB wall.** For the
 336 **ion and neutral densities we assume a linear change through the**
 337 **frictional transfer region:**

$$n_i(r) = n_i(d) \frac{r}{d} \quad (0 \leq r \leq d) \quad (8)$$

$$n_n(r) = n_n(0) + [n_n(d) - n_n(0)] \frac{r}{d} \quad (0 \leq r \leq d) \quad (9)$$

338 where the subscripts 0 and d respectively denote the EPB-side
 339 and ambient-side boundary of the frictional transfer region. With
 340 all these assumptions we obtain from the integral in Eq. (4):

$$\Delta P_n \approx \frac{d}{2} n_i(d) m_i v_i 4.45 \times 10^{-17} \left(\frac{n_n(0)}{3} + \frac{2n_n(d)}{3} \right) \sqrt{T_i} \quad (10)$$

341 We apply Eq. (10) to the EPB shown in Figure 1 around -10° latitude.
 342 For this we obtained a neutral particle pressure depletion of about 83 nPa. All
 343 the variables of Eq. (10) are known or can be read from Figure 1, except for v_i
 344 and d . When inserting them we obtain $v_i d = 3.7 \times 10^6$ (m²/s). Furthermore,
 345 we may estimate the thickness of the current sheet at the EPB wall from the
 346 magnetic field gradient. It took CHAMP about 5 s to pass the current sheet.
 347 With a spacecraft velocity of 7.6 km/s this amounts to 38 km. **As stated**
 348 **for Eq. (1), the current sheet originates from the plasma pressure**
 349 **(or, equivalently density) gradient, which exists in the transition**
 350 **region from the EPB to the ambient. Hence, it is expected that**
 351 **the current sheet thickness is comparable to that of the frictional**
 352 **transfer region, d .** Using the derived thickness, d , the relative ion-
 353 neutral velocity at the frictional transfer region takes a value of 97 m/s.
 354 We made assumptions on the plasma and neutral temperatures, which cause
 355 uncertainties in the estimated pressure values. The upcoming *Swarm* mission
 356 (<http://www.esa.int/esaLP/LPswarm.html>) consisting of 3 satellites, each of
 357 which is an upgrade of CHAMP, will measure ion/electron temperature and
 358 ion drift velocity as well as magnetic field, plasma density, and mass density.
 359 The mission is expected to give more precise answers to the question of EPB
 360 pressure balance.

361 **The observation of only three NDDs during June solstice may**
 362 **be explained by (10).** For this exercise we recall that our detection
 363 threshold is a filtered/rectified mass density change of 2.5×10^{-14} (kg/m³).
 364 The original mass density change (before filtering/rectifying) is expected to
 365 be about three times larger (e.g. compare Figures 1(a) and 1(d)). If $T_n = 800$
 366 K, the minimum neutral pressure change required for NDD identification is
 367 31 nPa. **As $\Delta P_n = k_B T_n \Delta n_n = k_B T_n (n_n(d) - n_n(0))$, Eq. (10) becomes:**

$$k_B T_n \Delta n_n \approx \frac{d}{2} n_i(d) m_i v_i 4.45 \times 10^{-17} (n_n(d) - \frac{\Delta n_n}{3}) \sqrt{T_i} \quad (11)$$

368 **We can solve it for Δn_n , from which the equation for ΔP_n is**
 369 **derived. With the minimum neutral pressure change calculated**
 370 **above ($\Delta P_n > 31$ nPa) we get the inequality:**

$$\Delta P_n = \left[\frac{1}{\frac{d}{2} n_i(d) m_i v_i 4.45 \times 10^{-17} \sqrt{T_i}} + \frac{1}{3 k_B T_n} \right]^{-1} n_n(d) > 31 \text{ (nPa)} \quad (12)$$

371 Here we apply the values derived above for v_i and d . The ion number
 372 density at the Appleton anomaly peaks is expected to be about 4 times (e.g.
 373 compare Figures 1(b) and 3(b)) the latitudinally/longitudinally averaged val-
 374 ues during June solstice, 6.0×10^5 (cm⁻³), given in Figure 3(b). **Therefore,**
 375 **we set $n_i(d)$ to be 2.4×10^6 (cm⁻³). We again assume $T_i = 800$ (K).**
 376 From Eq. (12) we can get the required ambient mass density:

$$\rho(d) = n_n(d) m_n > 5.6 \times 10^{-12} \text{ (kg/m}^3\text{)} \quad (13)$$

377 From this number we argue the following: even if NDDs are generated
 378 by ion-neutral collisions under the conditions of June 2002, many of them

379 would have depletion amplitude below our detection threshold, as the average
 380 neutral mass density in Figure 3(c) is lower than the minimum requirement
 381 given in Eq. (13). **Let us extend this argument in more general**
 382 **terms. As T_n , T_i , v_i and d are not measured by CHAMP let us use**
 383 **the values assumed above. Typical $n_i(d)$ is of the order of $10^{11} -$**
 384 **10^{12} m^{-3} according to Figure 3(b). With these values the bracket on**
 385 **the left side of Eq. (12) is dominated by the first term. Then, it can**
 386 **be stated from Eq. (12) that the product of ion number density and**
 387 **neutral mass density, $n_i(d)\rho(d)$, has to exceed a certain threshold**
 388 **so that detectable NDDs are created by EPBs. According to our**
 389 **initial estimation considering the above assumptions, the minimum**
 390 **value of $n_i(d)\rho(d)$ is $\sim 15 \text{ kg/m}^6$.**

391 In total, 131 NDDs were identified by our automatic detection proce-
 392 dure described in Section 2. The relative depths of NDDs and of EPBs are
 393 calculated as $(1 - \text{minimum density}/\text{maximum density})$ within ± 30 s around
 394 automatically identified events. Figure 4 is a scatter diagram comparing EPB
 395 and NDD relative depths in 2002-2005. First, it can be seen that NDD rel-
 396 ative depths are generally less than 0.05, which is about 5% of EPB depths.
 397 This result is consistent with *Bencze et al.* (2000), where the relative depths
 398 were less than 10% for most NDDs, and with *Schunk and Demars* (2003),
 399 where simulated NDDs had 1-3% amplitude for a wide range of background
 400 conditions. Second, we may suggest a general increase of NDD relative depth
 401 with increasing EPB depth. However, the large scatter implies that ambient
 402 conditions, such as neutral and plasma densities, as well as relative drift be-
 403 tween ions and neutrals in the frictional transfer region, are also important

404 factors for the NDD generation.

405 5. Summary

406 In this work we investigated neutral density depletions (NDDs) derived
407 from CHAMP accelerometer data at altitudes around 400 km. The following
408 characteristics are found in our study.

- 409 1. CHAMP observed NDDs for about 10-20 % of EPB encounters.
- 410 2. NDDs occur at latitudes north and south of the dip equator with an
411 offset of about 15° . On average, this location is collocated with the Ap-
412 pleton anomaly peaks and slightly poleward of EPB occurrence max-
413 ima.
- 414 3. The NDD occurrence maximizes around 21 LT, and has nearly died
415 out after 23 LT, while the EPB occurrence shows a broad maximum
416 between 20 LT-00 LT.
- 417 4. NDD occurrence rates are strongly dependent on the ambient neutral
418 and plasma densities. The dependence on the solar activity seems to
419 be intermediated by the ambient neutral and plasma densities.
- 420 5. All the results imply that an enhanced collision between ions and neu-
421 trals is needed for the NDD generation.
- 422 6. The product, ambient electron density times neutral mass density,
423 **has to exceed a certain value in order that detectable NDDs**
424 **emerge from EPBs. According to our initial estimation, the**
425 **threshold of $n_i(d)\rho(d)$ is ~ 15 kg/m⁶.** Generally, this is achived
426 only during years of elevated solar activity.

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Figure 1: An example of neutral density depletion (NDD): (a) neutral mass density at 10 s sampling, (b) plasma density measured by Planar Langmuir Probe (PLP), (c) residual magnetic field parallel to the mean field, (d) high-pass filtered/rectified signal of neutral mass density, and (e) residual magnetic field parallel to the mean field, which is high-pass filtered ($T_c=30$ s) and rectified.

Figure 2: Statistical distribution of NDD-to-EPB ratio: (a) global NDD distribution in equinoxes, (b) during June solstice, and (c) during December solstices. Panel (d) shows NDD-to-EPB ratio as a function of geomagnetic latitude and local time.

Figure 3: Time series of NDD occurrences and related parameters: (a) the number of NDD events per day during 2002-2005. Panel (b) nighttime (19-05 LT) plasma density averaged between $\pm 35^\circ$ geomagnetic latitudes. (c) averages of nighttime neutral density (normalized to 400 km altitude) within $\pm 35^\circ$ geomagnetic latitude, and (d) the solar flux index $F_{10.7}$.

Figure 4: Relation between EPB and NDD relative depths.