

# *Observations of the step-like accelerating processes of cold ions in the reconnection layer at the dayside magnetopause*

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### Article

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# Observations of the step-like accelerating processes of cold ions in the reconnection layer at the dayside magnetopause

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## 22 Abstract

23 Cold ions of plasmaspheric origin have been observed to abundantly appear in the  
24 magnetospheric side of the Earth's magnetopause. These cold ions could affect the magnetic  
25 reconnection processes at the magnetopause by changing the Alfvén velocity and the  
26 reconnection rate, while they could also be heated in the reconnection layer during the  
27 ongoing reconnections. We report *in situ* observations from a partially crossing of a  
28 reconnection layer near the subsolar magnetopause. During this crossing, step-like  
29 accelerating processes of the cold ions were clearly observed, suggesting that the inflow cold  
30 ions may be separately accelerated by the rotation discontinuity and slow shock inside the  
31 reconnection layer.

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32 **Key words:** cold ions, magnetic reconnection, ions acceleration of ions, magnetopause

## 33 Introduction

34 Cold ions (few eV) of plasmaspheric origin are often observed in the outer magnetosphere  
35 and the magnetospheric side of magnetopause, which are in the form of drainage plumes  
36 mainly driven there by convection electric field during the high geomagnetic activity [1-7],  
37 and are carried there by plasmaspheric wind via combinational consequence of corotation  
38 and convection electric field during quiet geomagnetic activity [6-11]. Cold ions from the  
39 polar ionosphere can also directly reach the dayside magnetopause along the magnetic field  
40 lines via outflow [12]. When the cold ions reach the dayside magnetopause, they may be  
41 involved in, and influenced by, magnetic reconnection in the magnetopause current sheet  
42 [5,13-17]. On reaching the magnetopause, it has long been thought to be lost to  
43 interplanetary space as the field lines are opened by reconnection [13, 18-22].

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44 The operation of MR is expected to result in a reconnection layer with characteristic ion and  
45 electron diffusion regions and an X-line of the central, null (zero) field and associated  
46 bundles of reconnected flux (flux tubes, moving in predictable ways from the magnetic

merging line) during periods of ongoing or intermittent reconnection [23-27]. Previous theories and simulations predicted that there are several boundaries within the reconnection layer, which can accelerate the ions at the associated area [28, 29]. Different models, however, predicted different boundaries [28, 29]. In the ideal MHD simulation, rotational discontinuities (RD), slow shocks or slow expansion fan (SS/SEF), and contact discontinuity (CD) are present in the reconnection layer [28], while in the hybrid simulation, the contact discontinuity cannot be identified due to the mixing of ions from the magnetosheath and magnetosphere, and slow shocks and slow expansion waves are modified [29]. At the magnetopause, the Alfvén wave is an intermediate wave or shock and transmitted through RD, thus, people often talk about RD and Alfvén wave together [30]. Observations confirmed the existence of the RDs and SS/SEF [31, 32]. Recent laboratory experiments and particle-in-cell simulations also suggested that the Hall effects can produce a strong electric field in the reconnection plane that is strongest across the separatrices, which separates the incoming field line region from the exhaust of reconnected field lines [33, 34]. Dipolarization fronts and flux ropes in the reconnection region of the magnetotail can also accelerate the particles, especially the electrons [35-39]. Clear separated acceleration signatures are difficult, despite recent access to multi-point sampling on small and meso-scale, owing to the fact that most of the encounters are highly dynamic. We report here one of the first, clear partial transitions through a reconnection layer near the subsolar magnetopause, which shows clear accelerations of the cold ions in the reconnection layer.

67

## 68 **Observations and Results**

69 Figure 1 summarizes conditions on 17 January 2013, where the IMF and solar wind data  
70 come from the NASA OMNIWeb and has been shifted 5 minutes from the nose of bow  
71 shock to the subsolar dayside magnetopause. The IMF was steadily southward after 17:00

72 UT ( $B_z \approx -10\text{nT}$ ), the solar wind dynamic pressure was initially typical ( $P_{\text{sw}} \approx 5\text{nPa}$ ) but  
73 then fell to unusually low values ( $\approx 0.1\text{nPa}$ ) (Fig. 1a and b). We have projected polar maps  
74 of ionospheric total electron into the equatorial plane using the same procedure as in Walsh  
75 et al. [40] (except a more adaptive magnetic field model [41] and magnetopause model [42]  
76 were used – see supplementary materials). This procedure has been used to compare the  
77 storm enhanced density (SED) plumes identified at low altitudes GPS total electron content  
78 (TEC) map with the plasmaspheric drainage plume determined by EUV imaging from the  
79 IMAGE spacecraft [43], and with the in situ plasma observations by THEMIS (Time History  
80 of Events and Macroscale Interactions during Substorms mission [44]) satellites [40], which  
81 indicated that SED plumes are associated with the erosion of the outer plasmasphere  
82 (plasmaspheric plume) by strong sub-auroral polarization stream (SAPS) electric fields [43,  
83 45]. Figure 1(c) is a keogram of the mapped TEC from the noon meridian as a function of  
84 time. Early in the time period, the high-density plasma plume from the dusk plasmasphere  
85 contacted the near-noon magnetopause but this was not the case later in the period (see also  
86 extended data in supplementary materials). The blue line in Fig. 1(c) is the inbound pass of  
87 spacecraft E of the THEMIS mission, which was close to the noon-midnight meridian and  
88 subsolar region (Fig. 1d and e). The mapping used in Walsh et al. [40] assumed that density  
89 variations in the topside ionosphere form fully field-aligned structures that map all the way  
90 to the equatorial plane. If this assumption is valid, THEMIS-E should have detected  
91 ionospheric plasma just inside the magnetopause during this pass. Figure 2 not only  
92 confirms that this was the case, it tells us about the subsequent evolution of this plasma.  
93 THEMIS-E first encountered energetic magnetospheric ions (see Fig. 2e at energy  $E \approx 10^4\text{eV}$ )  
94 around 18:17:50 and the magnetosheath current sheet at 18:21:50 (see Fig. 2a) when  $B_L$   
95 turns positive and the bipolar FTE signature in  $B_N$  is seen [40]. What we identify as  
96 accelerated ionospheric ions (see below) were first seen at 18:22:30 (Fig. 2e at  $E < 100\text{eV}$ )

97 causing the ion density  $N_i$  to be larger than even in the magnetosheath (Fig. 2b). Later,  
98 (18:28:30-18:29:50, 18:36:10-18:38:10 and 18:46:50-18:47:50) periods of closed field lines  
99 deep in the plasmashet (where ion temperature  $T_i$  is high and  $N_i$  low) were encountered,  
100 readily identified in Fig. 2(b) and 2(c). Between the first two of these periods the satellite  
101 returned to the reconnection layer (the regions between the two separatrixes of the  
102 reconnection) and observed a variable mixture of magnetosheath and magnetospheric  
103 plasma, however between the second two, the spacecraft remained in the magnetosphere and  
104 saw un-accelerated ionospheric ions ( $E < 20\text{eV}$  in Fig. 2e), which caused  $N_i$  to rise but  $T_i$  to  
105 fall without any sheath plasma being present. Thus THEMIS-E was seeing the arrival of the  
106 low energy plasma as Fig. 1(c) predicts it should.

107 There are some small intervals in these data that prove the putative ionospheric plasma in the  
108 reconnection layer does indeed come from the unaccelerated population seen in the outer  
109 magnetosphere. The first of these was a brief entry into an accelerated flow region near  
110 18:30 (when  $V_L$  briefly reached  $180 \text{ km s}^{-1}$ ), the second around 18:38:35 (when Fig. 2d  
111 shows  $V_L$  reached  $100 \text{ km s}^{-1}$ ). Figure 2(g)-2(l) concentrate on the second of these events.  
112 At 18:35:35 THEMIS-E observed a sharp transition from magnetosheath-dominated to  
113 magnetosphere-dominated plasma (Fig.2k and Fig.2l). There is no current sheet but a weak  
114 indication of accelerated flow in  $V_L$ . After this, the ionospheric component was seen at  $E <$   
115  $20\text{eV}$  but then weakened. The persistent negative  $V_N$  component (roughly approximate  $V_X$  in  
116 GSM coordinates, Fig.2j) reveals that this was caused by inward motion of the  
117 magnetopause. At 18:37:30,  $V_N$  was further negative, and this in-out motion of the  
118 magnetopause briefly returned the satellite to the reconnection layer. Figure 2(g) shows that  
119 the satellite crossed the current sheet twice (characterized by  $B_L$  components change the sign  
120 twice around 18:38:00 UT) with a strong guide field ( $B_M$  component). Figure 2(k) shows that  
121 low-energy ionospheric plasma was step-like accelerated up to about  $80\text{eV}$  and shows a

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122 reverse “U” type structure with steps around 18:38:30 UT before the sequence was reversed  
123 on the way out of the event. The accelerated flow had a peak magnitude of  $V_L \approx 100 \text{ kms}^{-1}$   
124 which corresponds to 63 eV energy for protons and hence the observed energy is consistent  
125 with the derived velocity moment (which assumes the ions detected were protons). The  
126 continuous energy increase on the way into and decrease on the way out of this event proves  
127 that the lower-energy ions in the accelerated flow region came from the ionospheric  
128 population seen in the magnetosphere near the magnetopause. The lack of any such  
129 dispersion for the higher energy ions seen during the event ( $E \approx 500 \text{ eV}$ ) shows they came  
130 from the magnetosheath due to the reconnection. The magnetosheath ions reached the  
131 spacecraft at about 18:38:27 UT (ion edge) and disappeared after about 18:38:45 UT (ion  
132 edge). The electron edge, first observation of magnetosheath electrons, is observed at about  
133 18:38:24 and 18:39:24 UT, which was referred as the separatrix of the reconnection layer  
134 [46, 47]. It is worth noting that the time duration between the latter electron and ion edges  
135 encountering was much longer than the former ones, which may be because the reconnection  
136 layer was slow down (the ion velocity clearly decreased (Fig. 2j)) and made THEMIS E stay  
137 much longer between the latter electron and ion edges.

138

### 139 **Discussions**

140 Figure 2(k) shows a reverse “U” type structure with steps for the low-energy ionospheric  
141 plasma around 18:38:30 UT. What happened there when the spacecraft crossed the  
142 magnetopause boundary? Vaivads et al. [46] suggested that there is an Alfvén edge or RD  
143 between the electron and ion edges on the magnetospheric side of the current sheet. From  
144 Fig. 2, we have identified two electron edges at about 18:38:24 and 18:39:24 UT, and two  
145 ion edges at about 18:38:27 and 18:38:45UT, respectively. If there is RD between electron  
146 and ion edges, we should observe clear rotations of the magnetic field when the spacecraft

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147 crossed the RD. We have plotted the 3D magnetic field vectors along the orbit tracks of  
 148 THEMIS E for the interval of 18:38:00-18:39:30 UT (Fig. 3a). From Figure 3a, we can find  
 149 the magnetic field was main in northward at the beginning, but started to rotate earthward  
 150 and duskward at about 18:38:25 UT, and then gradually rotated back from about 18:38:33  
 151 UT. These rotations of the magnetic field suggested there are RDs during this crossing. We  
 152 also have performed a Walén test for the interval of 18:38:19-18:39:35 UT and found there  
 153 is a good de-Hoffman-Teller (HT) frame for this reconnection layer with a velocity ( $V_{HT}$ ) of  
 154 278.16 km/s and [-0.49, -0.01, 0.87] in GSE coordinates, and a well Walén relation with a  
 155 slope of 0.98 between the Alfvén velocity and the residual plasma velocity in the HT frame  
 156 (Fig. 3b). These suggest that there was an RD at the magnetospheric side of the reconnection  
 157 layer indeed. Ideal MHD simulation suggested that the ratio of upstream and downstream  
 158 magnetic field can be used to identify that the discontinuity is a slow shock or slow  
 159 expansion fan by using the following equation [28, 31].

$$\eta = (B_2/B_1) = \{1 + \beta (1 - P_2/P_1)\}^{1/2}$$

161 where  $B_t$  is the discontinuity tangential magnetic field and  $P$  is particle pressure, and  
 162 subscripts 1 and 2 represent to upstream and downstream of the discontinuity. For a slow  
 163 shock (SS),  $\eta < 1$ , and for a slow expansion fan,  $\eta > 1$ , [28, 31]. In our case, the  $P_1$  is about  
 164 0.02 nPa and  $P_2$  is about 0.14 nPa, and the mean plasma  $\beta = 2P\mu_0/B^2 \approx 0.13$ , which gives  
 165  $\eta \approx 0.47$  and suggests this discontinuity is a slow shock. The basic characteristics of slow  
 166 shocks are that the magnetic fields are refracted towards the shock normal with a decrease of  
 167 their tangential component and total strength when the shock front passed them [28, 48]. In  
 168 our case, the magnetic field was refracted towards shock normal which is roughly  
 169 antiparallel to the boundary normal  $\mathbf{n}$  due to the magnetopause inward motion during the  
 170 interval of interest, and the tangential component (roughly  $B_L$ ) and total strength of the  
 171 magnetic field all decreased (Fig. 2 and Fig. 3a). Thus, these calculations and observations

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172 suggest that there were RD and SS been observed indeed when THEMIS E partially crossed  
173 the reconnection layer. These are consistent with the time elapsed since reconnection of the  
174 given field lines crossed.

175 Ion accelerations often occurred due to the dispersion of phase-steepened Alfvén wave  
176 and/or through shock drift acceleration or diffusion shock acceleration when they crossed an  
177 RD or SS [49]. Thus, the reverse “U” type structure in the low-energy ionospheric ions seen  
178 by THEMIS-E suggests that these ions were step-like accelerated by the boundaries within  
179 the reconnection layer, when the THEMIS-E crossed the separatrix, RD and SS on the  
180 magnetospheric side and the SS on the magnetosheath side, respectively (Fig. 4). The energy  
181 of the ions also seems step-like decrease when the spacecraft moved back and crossed these  
182 boundaries again to the magnetosphere due to the sunward and northward motion of the  
183 reconnection layer (schematic shown in Fig. 4). Although the 3s time resolution of the  
184 THEMIS data may tend to make the ion spectrum looks stepped, it still can clearly show  
185 that the accelerations associated with the boundaries within the reconnection layer make the  
186 ion energy sharply increase in a very short time interval.

187 To escape the magnetosphere, ions must reach beyond the tail reconnection site before the  
188 re-closure of magnetic field lines (as for the red trajectory in Fig.5). These ions will not  
189 receive as much (or any) of the Coriolis acceleration experienced by ions rising from the  
190 low-altitude cleft ion fountain source [50-52]. They are likely to be accelerated if the field  
191 line catches them up due to increased Alfvén speed at the magnetopause with increasingly  
192 negative  $X$ . The combined data clearly demonstrate a path for ionospheric plasma, collected  
193 in the outer plasmasphere, to enter into accelerated flow along the magnetopause driven by  
194 magnetic reconnection. All ion species in this region would have the velocity  $V_L$  of  $100 \text{ km s}^{-1}$   
195 near along the field line, but is this adequate for escape? The data on this day provide an  
196 estimate of how long the field lines remain open. At ionospheric heights, the ionization

197 tongue breaks up into polar cap patches and the TEC maps allow us to follow their evolution  
198 [53,54]. It has been shown [53, 54] that patches only escape the nightside polar cap and  
199 move onto sunward-convecting closed field lines when the field lines are reclosed in the tail.  
200 On the day studied here, as shown in Zhang et al. [53], this yields at least 2 hours before  
201 open field lines are reclosed. By then, if the accelerated ionospheric ions keep their velocity  
202 and move along the field lines, they would have moved at least  $113 R_E$   
203 ( $100 \times 2 \times 3600 / 6370 \approx 113 R_E$ ), placing them at  $X < -93 R_E$  down the tail (allowing for  
204  $20 R_E$  around the dayside magnetopause). Most estimates of even distant reconnection sites  
205 are at  $X \gg -90 R_E$ . It is therefore almost certain that the ionospheric ions seen here  
206 reaching the dayside magnetopause and being accelerated by reconnection did escape the  
207 magnetosphere. Thus, detached plasmaspheric plasma reaching a dayside magnetopause  
208 reconnection site would be very efficient at expelling large fluxes of ionospheric plasma into  
209 interplanetary space (schematic shown in Fig.5), if these plasmas gain enough energy  
210 (acceleration) and keep their velocity moving along the field lines. Because the GPS  
211 observations used here are routinely available, this opens up a genuine possibility of  
212 monitoring the loss of atmospheric material via this mechanism on a continuous basis and  
213 studying its variations with season and solar wind conditions.

214

## 215 **Conclusions**

216 Cold ions of plasmaspheric plume have been observed both in the projected GPS TEC data  
217 and in the *in situ* plasma data from THEMIS satellite near the dayside magnetopause.  
218 THEMIS-E partially crossed a reconnection layer near the subsolar magnetopause and  
219 clearly observed step-like accelerating processes of these cold ions. The observations  
220 suggest that the inflow cold ions may be separately accelerated by the rotation discontinuity  
221 (or Alfvén wave) and slow shock inside the reconnection layer.

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361 **Figure Captions:**

362 **Fig. 1.** (Color online) Data from 17 January 2013. (a) The interplanetary magnetic field X, Z  
 363 and Y components (in the GSM frame). (b) The solar wind dynamic pressure PSW. (c) A  
 364 keogram showing total electron content mapped from the noon meridian to the equatorial  
 365 plane using the Tsyganenko T96 model [41], as a function of time. The black line shows the  
 366 magnetopause position from a different model [42] and the blue line the path of THEMIS-E.  
 367 (d) and (e) The orbit tracks of THEMIS-E relative to the modelled magnetopause position in  
 368  $XZ_{GSE}$  and  $XY_{GSE}$  plane (GSE is geocentric solar ecliptic coordinate system).

369 **Fig. 2.** (Color online) THEMIS-E spacecraft data for (a-f) 18:10-18:50 and (g-l) detail of  
 370 18:35-18:40. Fields and flows are shown in magnetopause (MP) aligned “LMN” coordinates  
 371 during the time interval around the MP crossing of the spacecraft (about 18:38:07-18:38:32  
 372 UT), where N is the magnetopause normal, L is in the  $(Z_{GSM}, N)$  plane and M completes a  
 373 left-handed set (GSM is the geocentric solar magnetic coordinate system) with  $\mathbf{l} = (0.77, -$   
 374  $0.03, 0.64)$ ,  $\mathbf{m} = (-0.63, 0.14, 0.76)$  and  $\mathbf{n} = (0.11, 0.99, -0.09)$  in GSM coordinates. (a and  
 375 g) Magnetic field components ( $B_L$ ,  $B_M$  and  $B_N$  in blue, green and red); (b and h) ion density,  
 376  $N_i$ ; (c and i) ion temperature,  $T_i$ ; (d and j) ion velocities ( $V_L$ ,  $V_M$  and  $V_N$  in blue, green and red);  
 377 (e and k) and (f and l) ion and electron energy-time spectrogram of differential energy flux  
 378 for all pitch angles, respectively. The associated regions, crossed by the spacecraft, are  
 379 presented as horizontal thick color lines with labels below panels f and l.

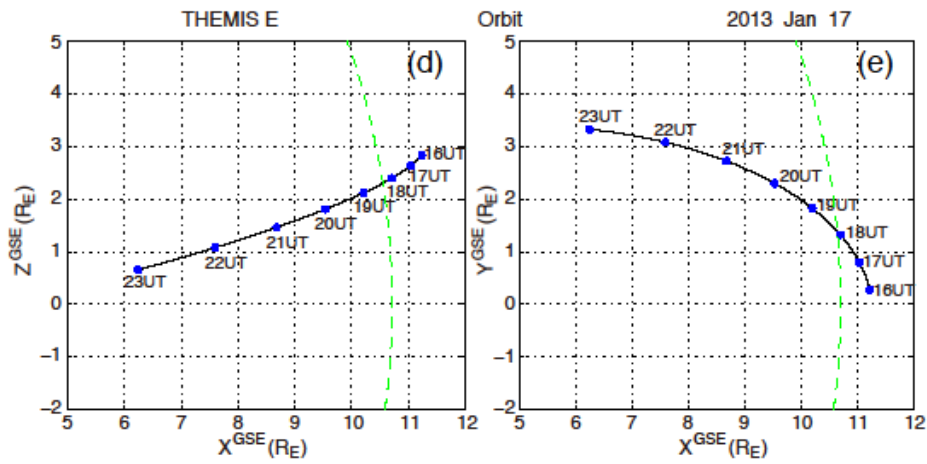
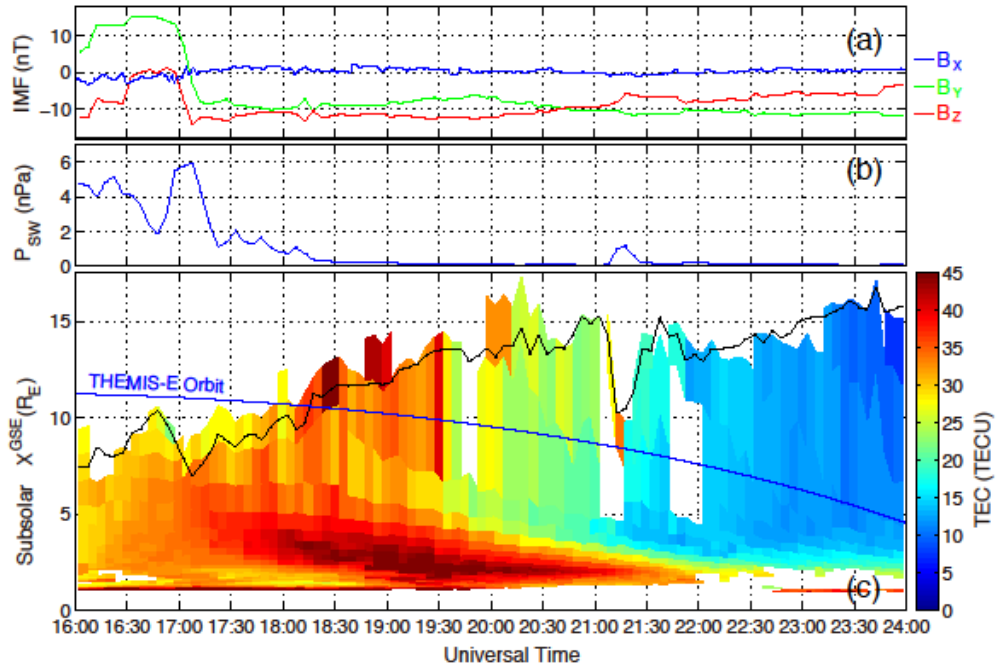
380 **Fig. 3.** (Color online) A 3D plot of the magnetic field data and a Walén test of plasma data  
 381 measured by THEMIS E. (a) The 3D magnetic field vectors in GSE coordinates along the  
 382 orbit tracks of THEMIS E for the interval of 18:38:00-18:39:30 UT. The vectors have been  
 383 separated and colored every 30 seconds. The blue and magenta vectors (with arrows) present  
 384 the directions of deHoffmann-Teller frame velocity ( $V_{HT}$ ) and the mean boundary normal  $\mathbf{n}$ .  
 385 (b) A Walén test of the reconnection layer crossing for the interval of 18:38:19-18:39:35 UT.

386 The colored dots represent the three components of the velocity in GSE coordinates (Red for  
387  $V_x$ , green for  $V_y$ , and blue for  $V_z$ ).

388 **Fig. 4.** (Color online) Schematics of the structure of the reconnection layer and the  
389 acceleration processes of the ions on the trajectory of the spacecraft. An asymmetrical  
390 reconnection layer is often seen on the dayside magnetopause since the plasma and magnetic  
391 field parameters are different in the magnetosphere (Msp) and magnetosheath (Msh).

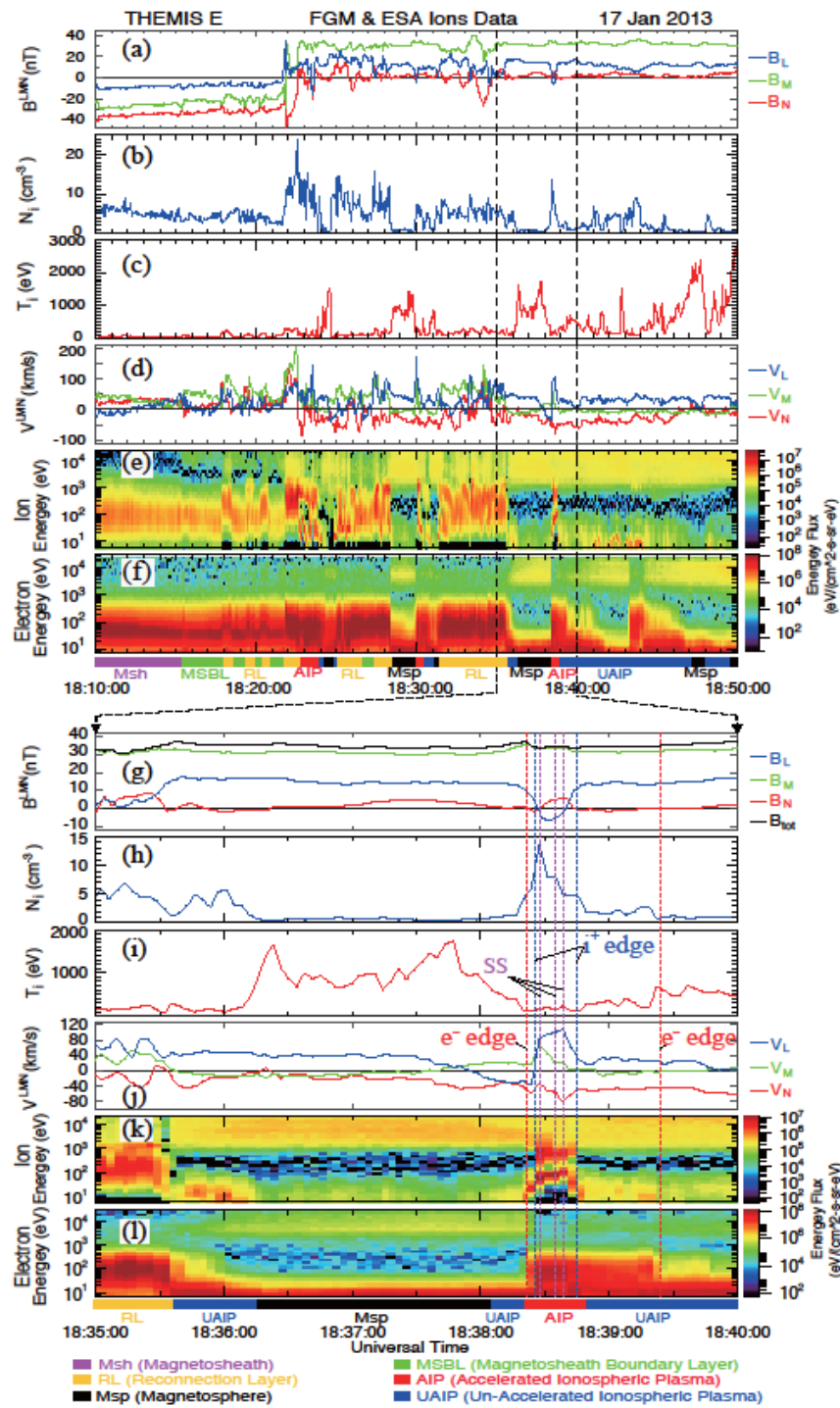
392 **Fig. 5.** (Color online) Schematics of ionospheric ion outflow. The X direction, from the  
393 centre of the Earth to the centre of the Sun, is to the left. The brown line is the outer  
394 boundary of the magnetosphere, the magnetopause, inside which are three distinct regions:  
395 the tail lobes (black) contain “open” magnetic field lines that thread the magnetopause which  
396 are generated in the Dungey cycle during periods of southward IMF by magnetic  
397 reconnection at the dayside magnetopause (at the yellow dot) and re-closed by reconnection  
398 in the tail (at the red dot) [23]. The plasmasheet (dark grey) contains closed field lines which  
399 connect the ionospheres in the two hemispheres and never thread the magnetopause. Closed  
400 field lines convect sunward in the Dungey cycle. The plasmasphere (in white) is also on  
401 closed field lines and has higher plasma densities than the plasmasheet because magnetic flux  
402 tube volumes are smaller and can be filled by outflows from the ionosphere. The coloured  
403 lines show trajectories for ions of plasmaspheric origin from reconnection acceleration region  
404 (see text). Note that all ions are moving along the magnetic field lines but trajectories are not  
405 field-aligned because the field lines move as part of the Dungey convection cycle. Higher  
406 energy ion trajectories (red arrows) are closer to field aligned than lower energy ones (in  
407 mauve) because they have higher field parallel velocity.

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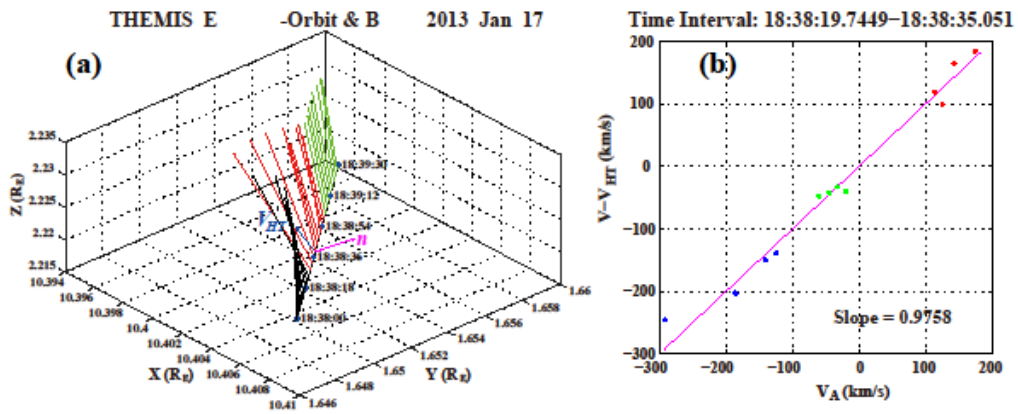


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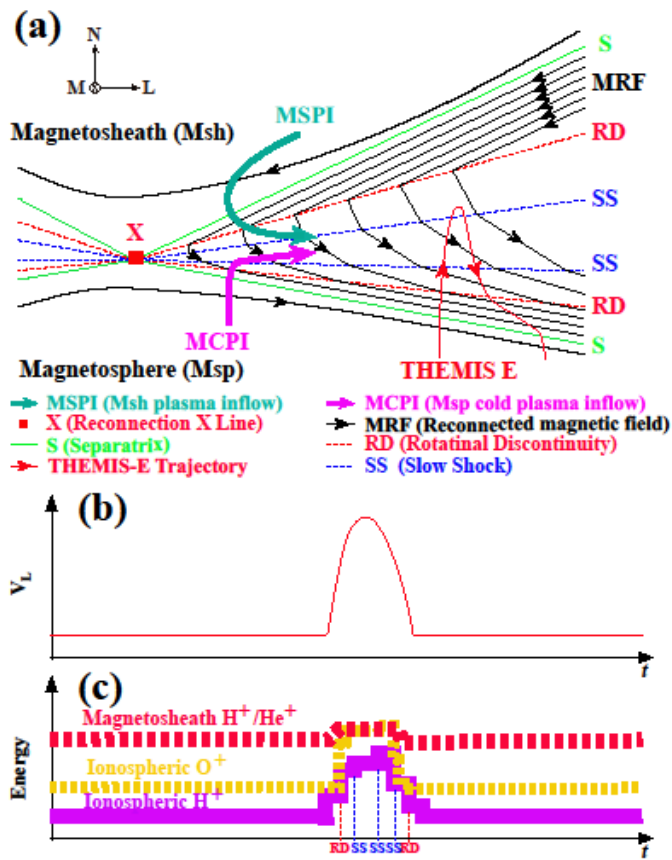


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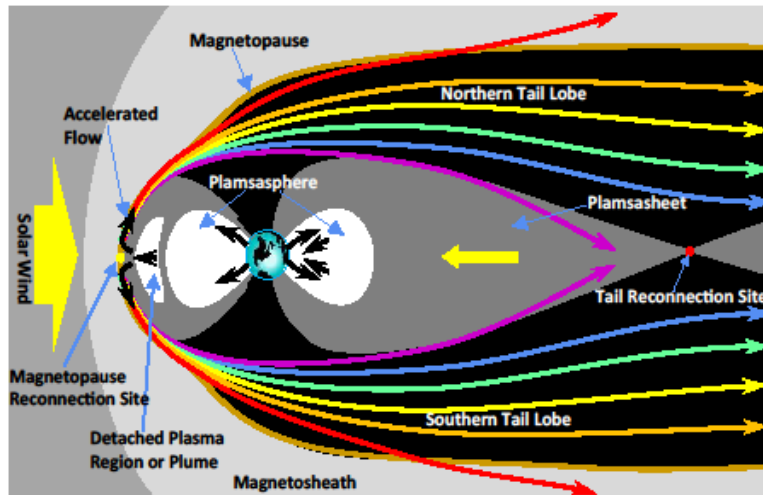
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