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Abstract

Conjunction observations of the electromagnetic field and plasma by Cluster and TC-1 at the dayside magnetosphere are presented to investigate the sequential flux ropes transferred from the low latitude boundary layer (LLBL) to the high altitude cusp on 10 March 2004.Three sequential flux ropes originating from the dayside low latitude magnetopause are first detected by TC-1. After ~ 6 min, three sequential flux ropes accumulated with energetic oxygen ions are also detected by Cluster in the high altitude cusp. The recurrence period of these flux ropes is ~ 3 min. The number density of energetic oxygen ions in the cusp flux rope is ~ 0.25 cm^{-3} detected from CIS/CODF instrument on Cluster. It is found that oxygen ions with energy lager than 10 keV have a narrow pitch angle (less than 90 degree) distribution in the southern high altitude cusp. While oxygen ions with energy less than 10 keV are distributed in a wide pitch angle from 0 to 180 degree. Counter-streaming energetic oxygen ions are found in these flux ropes in the high altitude cusp .This result suggests that the oxygen ions with energy less than 10 keV in the high altitude cusp have two source regions. One is from the dayside magnetopause and the other is from the low altitude cusp. Our investigations provide evidence that flux ropes at dayside low latitude magnetopause can carry energetic oxygen ions into the high altitude cusp region.

Three key points

1) Counter-streaming oxygen ions are observed in the flux ropes in the cusp.

2) Energetic oxygen ions accumulated within sequential flux ropes in the high-altitude cusp.

3) Conjunction observations present sequential FTEs transfer from the dayside LLBL to the cusp.

1. Introduction

The cusp is one of important source regions of single charge oxygen ions, O^+, in the magnetosphere. The outflow of oxygen ions can be observed in the whole cusp region [e.g.,Yau et al.,1985; Yau and Andre,1997; Yau etal.,2007]. The energy of the outflow oxygen ions is around 300 eV at the middle altitude cusp [e.g., Yau et al., 2007]. But oxygen ions with energy above 1 keV have been observed in the high altitude cusp regions [e.g., Slapak, et al., 2011; Kristler, et al., 2010]. There are many debates on the source of energetic oxygen ions in the high altitude cusp region [e.g., Chen and Fritz, 2001; Fritz et al., 2003; Lindstedt et al., 2011; Trattner et al., 2011]. Lindstedt et al. [2010] proposed that the oxygen ions can be locally accelerated by the perpendicular electric field in the high altitude cusp. Chen and Fritz [2001] reported that energetic oxygen ions were from the ionosphere and energized at the high altitude cusp. On the other hand, Trattner et al. [2011] pointed out that the energetic oxygen ions were originated from the forth shock ahead magnetosheath.

The Flux Transfer Events (FTEs) originated from the low latitude dayside magnetopause can move along the magnetopause to the high latitude cusp region [e.g., Akhavan-Tafti et al.,2018; Cowley 1982; Lee and Fu, 1985; Roux et al., 2015]. Flux ropes or open flux tubes are usually adopted as the description of FTEs [e.g., Duan et al., 2015; Eastwood et al., 2016; Lee and Fu, 1985; Roux et al., 2015, Sun et al., 2019; Xiao et al., 2004; Zhang et al.,2010]. Lee and Fu [1985] reported that multiple X-line reconnection gave rise to multiple flux ropes at the dayside magnetopause. Omidi and Sibeck [2007] proposed that multiple FTEs with a various sizes are formed at LLBL and traveled along the magnetopause surface into high latitude polar region during southward IMF. The periodicity of sequential FTEs is in the range from 1.5 min to 18.5 min with average value of 8 min and common value of 3 min [e.g., Trattner et al., 2012; Rijnbeek et al., 1984; Lockwood and Wild, 1994]. Cowley [1982] reported that the travel time of FTEs from the subsolar magnetic reconnection region to the vicinity of the cusp was around 5 min. The low latitude flux ropes propagate towards southward and northward high latitude region with different bipolar signatures [e.g., Berchem and Russell, 1984; Le et al., 2008]. Le et al. [2008] pointed out that the southward moving flux tube produced a bipolar signature with inward/outward (-/+) polarity.

The scale size of flux ropes at the dayside magnetopause is in the range from a few hundred kilometers to about an Earth radius [e.g., Akhavan-Tafti et al., 2018; Lee and Fu, 1985; Eastwood et al., 2016; Sun et al., 2019]. Akhavan-Tafti et al. [2018] reported that the mean diameter of FTEs was ~1700km at the Earth's subsolar magnetopause. Eastwood et al. [2016] reported that ion-scale flux ropes with scale size ~1100 km were observed by MMS at the dayside magnetopause. Ten keV energetic oxygen ions near the dayside magnetopause have gyroradius around ~1000 km. These energetic oxygen ions may be captured into the flux ropes and transported form low latitude to high latitude region. Phan et al. [2004] reported that energetic O+ with energy larger than 3keV in the reconnection jets are observed by Cluster at the duskside mid-latitude magnetopause under steady southward IMF condition.

In this paper, the conjunction observations of TC-1 and Cluster present a clear chain for sequential FTEs transport from the LLBL to the high altitude cusp. We focus on the sequential FTEs accumulated with energetic oxygen ions in the high altitude cusp observed by Cluster. They both observed sequential FTEs with interval time period of ~ 3 min. In the second section the observations of sequential FTEs near the dayside magnetopause by TC-1 and FTEs accumulated with energetic oxygen ions in the high altitude cusp by Cluster are presented, respectively. Discussions and summary are shown in the last section.

2. Conjunction observations of FTEs

2.1 Sequential Flux ropes observed by TC-1 at the LLBL

Figure 1 shows plasma and magnetic field data from TC-1 located near the dayside magnetopause. From top to bottom, the panels show that (a) ions number density, (b) ions temperature, (c) plasma beta value β, (β is the ratio of plasma thermal pressure to the magnetic pressure, $\beta=2\mu_0 nT/B^2$), (d) to (f) the x, y, and z component of ions velocity, (g) to (i) the z, x, and y component (grey line) and the total magnitude (black line) of magnetic field. The position of TC-1 located near dayside low latitude magnetopause is presented at the bottom in Figure 1. The two vertical red lines mark the time intervals of the continuous negative B_z component from 10:53:00 UT to 11:14:00 UT. The minimum value of B_z component is about - 40 nT. During this interval the ions number density is high (larger than 10 cm^{-3}) as shown in Figure 1a. The maximum value of ion number density is about 25 cm^{-3}. Ion temperature is low (less than 1 keV) as shown in Figure 1b. Ions velocity in the X direction is negative and slow, Vx ~ -100 km/s. Those parameters indicate that TC-1 is located at the dayside magnetosheath-side of the low latitude boundary layer. Figure 1f presents that the B_x component has bipolar signatures. This may be associated with the magnetic reconnection at the dayside magnetopause. So we display the magnetic field and ions velocity in the local boundary normal coordinate system (LMN) in Figure 2.

Figure 2 shows three components of the magnetic field and proton velocity in LMN coordinate system. From top to bottom, the panels display the B_N, B_M , B_L component , and the total magnitude Bt of the magnetic field, the v_N,v_M, v_L component and the total magnitude vt of the ions velocity, respectively. The normal vector **N** = (0.93, 0.26, -0.25) (GSM) is determined as the minimal variation direction of the magnetic field in the interval from 10:56:50 UT to 10:59:56 UT. The vectors **M** and **L** are defined as $\mathbf{M} = \mathbf{N}\times\mathbf{Z}_{GSM}$ and $\mathbf{L} = \mathbf{M}\times\mathbf{N}$. In Figure 2 three green shade regions demonstrate that the B_N firstly decreases then increases, the B_M sharply increases and the significant increase in the magnetic total value, Bt. These three regions mark three flux ropes observed by TC-1 near the dayside low-latitude magnetopause. They are signed as $FR_{A1,}$ FR_{B1} and FR_{C1} shown at the topside of Figure 6, respectively. The first flux rope marked by FR_{A1} has large negative B_N then decrease suddenly at 10:52:20 UT. The second and third flux ropes marked by FR_{B1} and FR_{C1} have distinct B_N bipolar signature from negative to positive and larger total value of magnetic field at10:56:20 UT and 10:58:50 UT respectively. The location of TC-1, ~ (10.51,-0.28,-1.57) R_E, at the bottom of Figure 2 shows that the spacecraft located in the southward hemisphere side of subsolar point. The negative to positive bipolar signatures imply that flux ropes are from the subsolar point magnetic reconnection and propagate toward the southward hemisphere [Le et al., 2008]. These three flux ropes are all accompanied with down-tail ions bulk flow, as shown in Figure 2e and 2g.

2.2 Energetic oxygen ions within Sequential Flux ropes in the high-altitude cusp

Figure 3 presents the plasma and magnetic field observed by Cluster C4 at southern hemisphere high latitude region around (3.7,-4.4,-9.8) Re. From top to bottom, the panels show the number density of (a) proton, (b) helium ions He^{++}, and (c) oxygen ions O^{+}, (d) proton temperature, (e) plasma beta value, β, (f) the x component of proton velocity, (g) to (i) the x and z component of the magnetic field, the magnetic field total magnitude (black line) and the By component (blue line), respectively. During the intervals of 10:57 UT to 11:09 UT, Figure 3b presents that the He^{++} number density is larger than 0.5 cm^{-3}. At the same time period, Figure 3f displays the proton vx component value decrease to around ~100 km/s and in the tailward direction. Figure 3i shows the total magnetic field magnitude decreases and with significant fluctuations. Those parameters demonstrate that Cluster C4 is crossing the high altitude cusp. At 10:57:30 UT, the Bx and Bz components change from positive value to negative value which as marked by the first pink vertical dashed line. After this time Cluster C4 enters into the southern high altitude cusp region. Figure 3c presents three sharp increases in the number density of O^{+} ions in the high altitude cusp, as marked by three vertical red lines in Figure 3. The maximum value of O^{+} ions number density is about 0.27 cm^{-3} in the cusp. Corresponding these oxygen ions number density increase, the magnetic field total value also increases and the B_z component has bipolar signature as shown in the last two panels, Figure 3i and 3h, respectively.

Figure 4 presents the oxygen ions energy flux spectrum and pitch angle distribution in the intervals of 10:30 UT to 11:30 UT. The first panel shows the oxygen ions energy flux from 40 eV to 40 keV. The next three panels show oxygen ions pitch angle distributions in three energy channel 40 eV to1 keV, 1 keV to 10 keV, 10 keV to 40 keV, respectively. The interval between the two pink vertical dashed lines is the time of Cluster crossing the high altitude cusp. Figure 4a clearly demonstrates that energetic oxygen ions with energy larger than 10 keV are found in the high altitude cusp region. They are especially marked by the three dotted vertical lines in Figure 4. The pitch angle distribution of high energy oxygen ions, >10 keV, presented in Figure 4d, shows that these O^{+} ions are dominated in the pitch angle less than 90 degree. It means that those O^{+} ions almost outflow from the low altitude cusp in the southern hemisphere. On the other hand, oxygen ions with energy less than 10 keV are distributed in a wide pitch angle range from 0 to 180 degree, as shows in Figure 4b and 4c. According to the energetic O^{+} ions with sharp increase in the energy flux and number density, we present the magnetic field and proton velocity in the LMN coordinate system in the cusp, as shown in Figure 5.

Figure 5 presents three flux ropes observed by Cluster C4 in the high altitude cusp region, which are marked by three green shade regions, FR_A, FR_B and FR_C (shown at the topside of this figure) , respectively. From top to bottom, the panels show oxygen ions density, helium ions density, three components of the magnetic field and proton velocity in a LMN coordinate system, B_N, B_M and B_L, v_N,v_M and v_L, respectively. The normal vector **N** = (-0.43, 0.02, 0.90) (GSM) is determined as the minimal variation direction of the magnetic field in the intervals from 11:00:45 UT to 11:01:45 UT. Figure 5a shows that these three flux ropes are accumulated within the high density of oxygen ions, n_{o+} ~0.25 cm^{-3}, in the high altitude cusp. The B_N component has bipolar signals at around 10:58:20UT, 11:02:20UT and 11:04:50UT, as shown in Figure 5c. The total magnetic magnitude increases significantly at these three times, as presented in Figure5f. These flux ropes all have negative V_L value as shown in the bottom panel. These features of the magnetic field show that three flux ropes are observed in the high altitude cusp regions with a period of ~ 3 min.

The wide range of the pitch angle distribution of energetic oxygen ions in the high altitude cusp shown in Figure 4b and 4c means that these oxygen ions are from two different regions. The 2D cut of oxygen ions velocity distributions can clear reveal that the energetic O^+ ion are characterized with the counter-streaming flows. Figure 6 shows the velocity distributions of oxygen ions with energy in the range of 40 eV to 40 keV at 10:59:24 UT, 11:02:28 UT and 11:05:53 UT, respectively. Within these three flux ropes oxygen ions have counter-streaming features, which are both presented in Figure 6b and 6c. The right three panels of Figure 6 show that oxygen ions have large counter -direction velocity in the Z direction at 10:59:24 UT, 11:02:28 UT and 11:05:53 UT respectively. The total magnitude of O^+ ions velocity is around 600 km/s. These three times are in the time intervals of the magnetic flux ropes in the high altitude cusp region which are shown in Figure 5 as three green shade regions, respectively. They have one-to-one corresponding relationship. These counter-streaming oxygen ions in three flux ropes demonstrate that they are from two difference regions. They consist of the ionosphere outflow and magnetopause magnetic reconnection precipitation.

3. Summary and discussions

The above conjunction observations of TC-1 at the LLBL and Cluster at the high altitude cusp regions are adopted to investigate the sequential FTEs transporting from the subsolar dayside magnetopause to the high altitude cusp. The results demonstrate that the energetic oxygen ions have counter-streaming in the high altitude cusp regions. These oxygen ions have two different source origins. One is from the ionosphere outflow. The other is the oxygen ions precipitation originating from the magnetic reconnection region at the low latitude dayside magnetopause. As displayed in Figure 5, there are three flux ropes observed by Cluster C4 at high-altitude cusps about ~5-6 minutes delay from those by TC-1 at 10:58:20 UT, 11:01:20 UT and 11:04:50 UT, respectively, which are presented by three green shaded regions marked by FR_A, FR_B and FR_C, respectively. Thus, these conjunction observations of sequential FTEs suggest that the high-latitude Flux ropes in the cusp are from the dayside low-latitude magnetopause reconnection. On the other hand, the velocity distributions in these flux ropes as shown in Figure 6 present ions precipitation in the high-altitude cusps with the large v_z value. Ions precipitation along the magnetic field has been used to induce the magnetic reconnection process. The ions precipitation also implies that these three cusp flux ropes are origin from the dayside low-latitude magnetopause reconnections. Phan et al. [2004] reported that energetic oxygen ions with high density 0.2-0.3 cm^{-3} in the reconnection jets are observed by Cluster at the dayside magnetopause under the steady southward IMF. Our results that the sequential FTEs accumulated with high number density 0.25 cm^{-3} of energetic oxygen ions in the high altitude cusp maybe associated with the similar reconnection at the LLBL reported by Phan et al. [2004].

The delay time ~ 5-6 min from the LLBL flux ropes (FR_{A1}, FR_{B1} and FR_{C1}) observed by TC-1 to the high altitude cusp flux ropes (FR_A, FR_B and FR_C) observed by Cluster is consisted with the propagating time of FTEs from LLBL to cusp in previous reports [e.g., Cowley, 1982]. According toTC-1 observations, the background magnetic field magnitude 60 nT and the ions density 16 cm^{-3} as presented in Figure 1i and 1a, the Alfvén speed can be calculated is ~ 327 km/s. Based on the locations of TC-1 at the bottom of Figure 1, TC-1 observed FTEs at the LLBL with X~10.4 R_E, we can calculate the time interval of FTEs transporting from the LLBL to the high altitude cusp being ~ 5.3 min. This calculating time interval of FTEs transporting from the LLBL to the high altitude cusp is consistent with that of conjunction observations between TC-1 at the LLBL and Cluster in the cusp time intervals, from 10:52:20 UT to10:58:40 UT, 10:56:20 UT to 11:01:20 UT and 10:58:50 UT to 11:04:50 UT.

Energetic oxygen ions with tens keV energy have large Larmor radius, ~ several thousand km, in the high altitude cusp. This spatial scale is closed to FTEs radius size in a few thousands km. Those energetic oxygen ions can be trapped in these flux ropes and move along the magnetopause to the high altitude cusp with the same velocity of FTEs. Eastwood et al. [2016] reported that ion-scale flux ropes with ~1100 km generated by the magnetic reconnection are observed by MMS at dayside low latitude magnetopause. Using 2.5-D global hybrid simulations, Omidi and Sibeck [2007] proposed that multiple FTEs with a various sizes are formed at LLBL and traveled along the magnetopause surface into high latitude polar region during southward IMF. The energetic oxygen ions in our event maybe origin from ring current during the recovery phase of the median storm on 9 March, 2004 (Dst ~-80 nT). They escape into the low latitude magnetopause by guiding center magnetic field. These energetic oxygen ions located in flux ropes as the reconnection jets. The energetic oxygen ions with high number density observed in the reconnection jet are also reported by Phan et al. [2004]. Tens keV energetic oxygen ions with large gyroradius of ~ 1000km, which is close the radius of flux ropes, are trapped in FTEs propagating to high latitude cusp and then to high latitude magnetotail region. Duan et al. [2015] reported that flux ropes accumulated with energetic oxygen ions observed by Cluster at high latitude nightside magnetotheath were from the high altitude cusp.

As addressed above, the conjunction observations of the sequential flux ropes at the low latitude boundary layer by TC-1 and at the high altitude cusp by Cluster are investigated in our paper. The main conclusions of our observations can be drawn as follows. The delay time of these sequential flux ropes from the low latitude magnetopause to the high altitude cusp is around 5-6 min. These sequential flux ropes are accumulated with energetic oxygen ions observed by Cluster in the high altitude cusp. The number density of energetic O^+ ions, detected by CIS/CODF instrument on Cluster, is very high in these sequential flux ropes, ~ 0.25 cm^{-3}. These O^+ ions with different energy have different pitch angle distribution in the high altitude cusp. The oxygen ions with energy lager than 10 keV are dominantly distributed in the quasi-parallel direction along the background magnetic field in the southern high altitude cusp. While O^+ ions with lower energy less than 10 keV have a wide range of pitch angle distribution from 0 degree to 180 degree. This reveals that oxygen ions with energy less than 10 keV in the high altitude cusp are from two different regions, the dayside low latitude magnetopause and low altitude cusp region. Our investigations present evidence that the sequential flux ropes at dayside low latitude magnetopause can carry oxygen ions into the high altitude cusp region.

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Figures and Captions

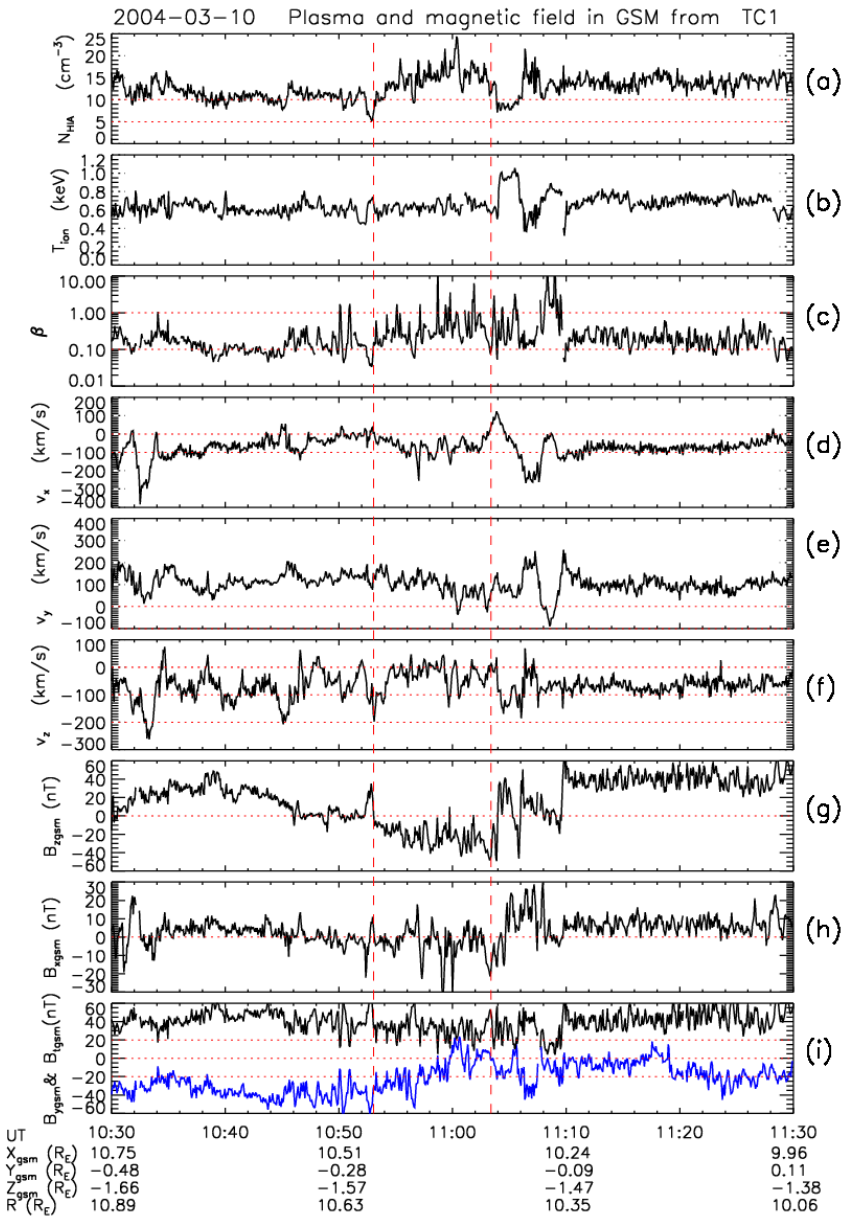

Figure 1 The plasma and magnetic field parameters are from TC-1 HIA and FGM during the period of 10:30 UT to 11:30 UT 10 March 2004. From top to bottom, panels are (a) ions number density, (b) ions temperature, (c) plasma beta value, β, (d) to (f) the vx ,vy and vz component of ions, respectively,(e) plasma beta value, β, (f) the x component of proton velocity, (g) the B_x component of magnetic field, (h) the B_z component, and (i) the B_y (blue line)and total magnitude of magnetic field.

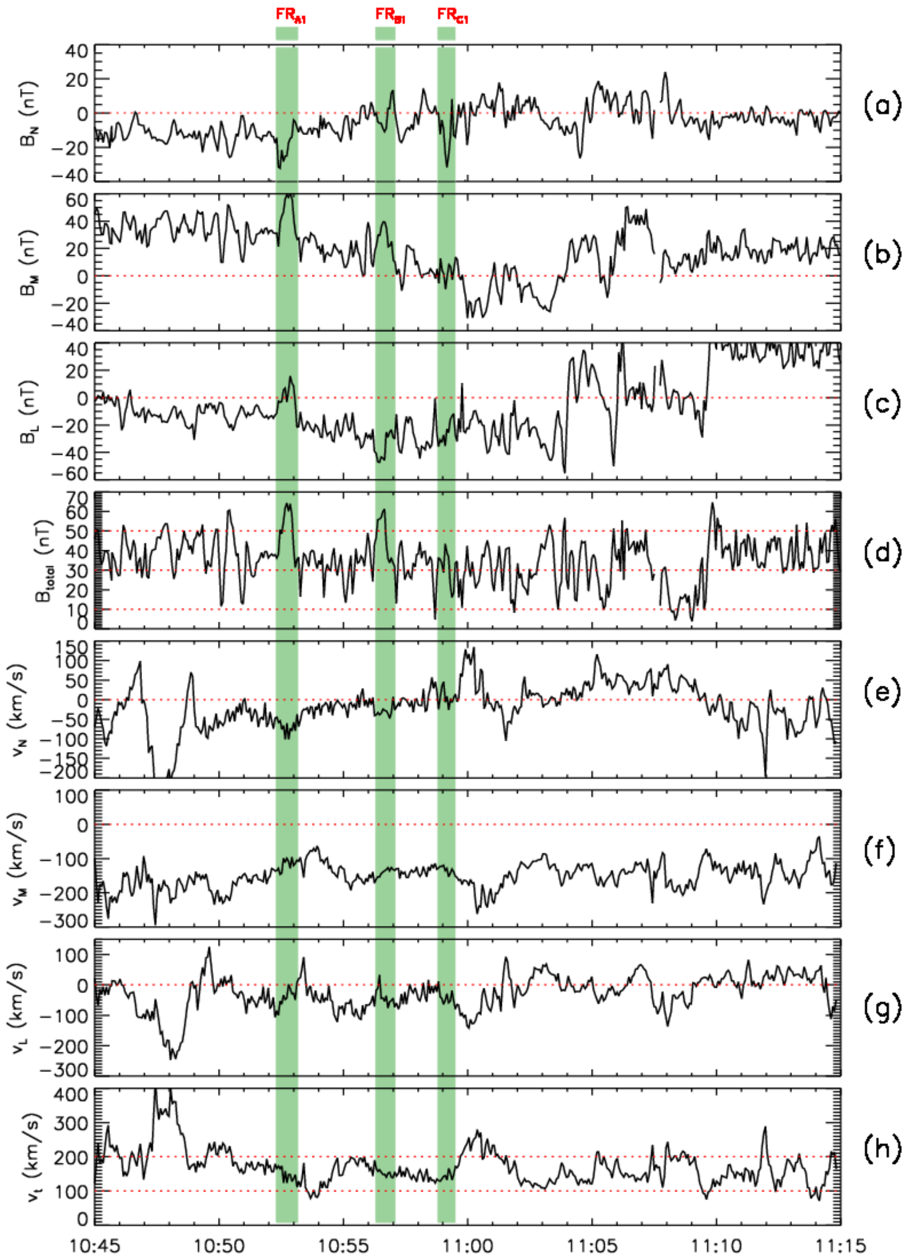

Figure 2 Sequential Flux ropes observed byTC-1 at the dayside low latitude boundary layer under the southward Bz component. From top to bottom, the panels are (a) the magnetic field B_N component, (b) the B_M component, (c) the B_L component, (d) the total magnitude of the magnetic field, B_t, (e) to (h) proton velocity v_N,v_M,v_L component and the total magnitude v_t, respectively. Three green shade regions mark the intervals of sequential flux ropes observed by TC-1 at LLBL as FR_{A1}, FR_{B1}, FR_{C1} at the top side of Figure 2, respectively.

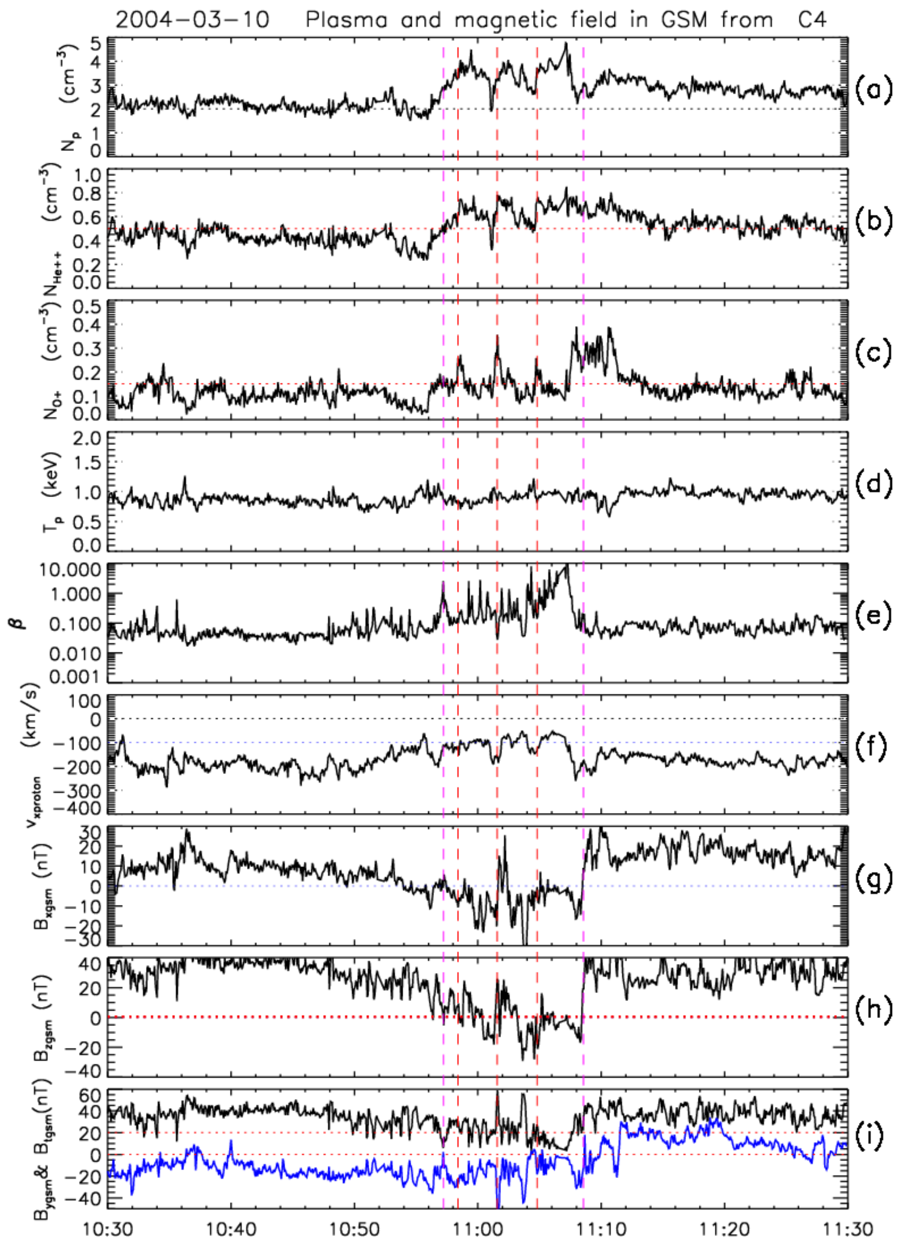

Figure 3 The plasma and magnetic field parameters are from Cluster C4 CIS/CODIF and FGM during the period of 10:30 UT to 11:30 UT 10 March 2004. From top to bottom, panels are (a) proton number density, (b) He^{++} number density, (c) O^+ number density, (d) proton temperature, (e) plasma beta value, β, (f) the x component of proton velocity, (g) the B_x component of magnetic field, (h) the B_z component, and (i) the B_y (blue line) and total magnitude of magnetic field. Three red dashed vertical lines mark the time of high number density of O+ ions in the high altitude cusp.

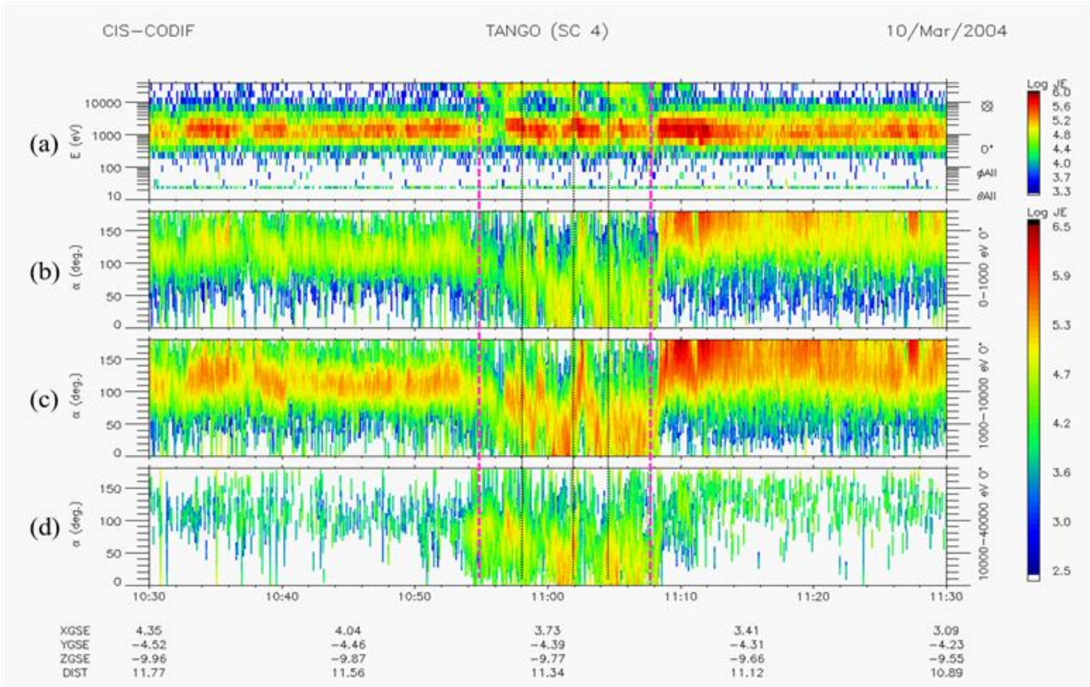

Figure 4 The O^+ ion energy spectrogram flux and pitch angle distribution obtained from CODIF (energy range is from 40 eV to 40 keV) on 10 March 2004. (a) O+ energy spectrogram of omnidirectional flux, (b) to (d) O^+ pitch angle distribution with energy in the range of 40 eV to 1 keV, 1 keV to 10 keV, and 10 keV to 40 keV, respectively.

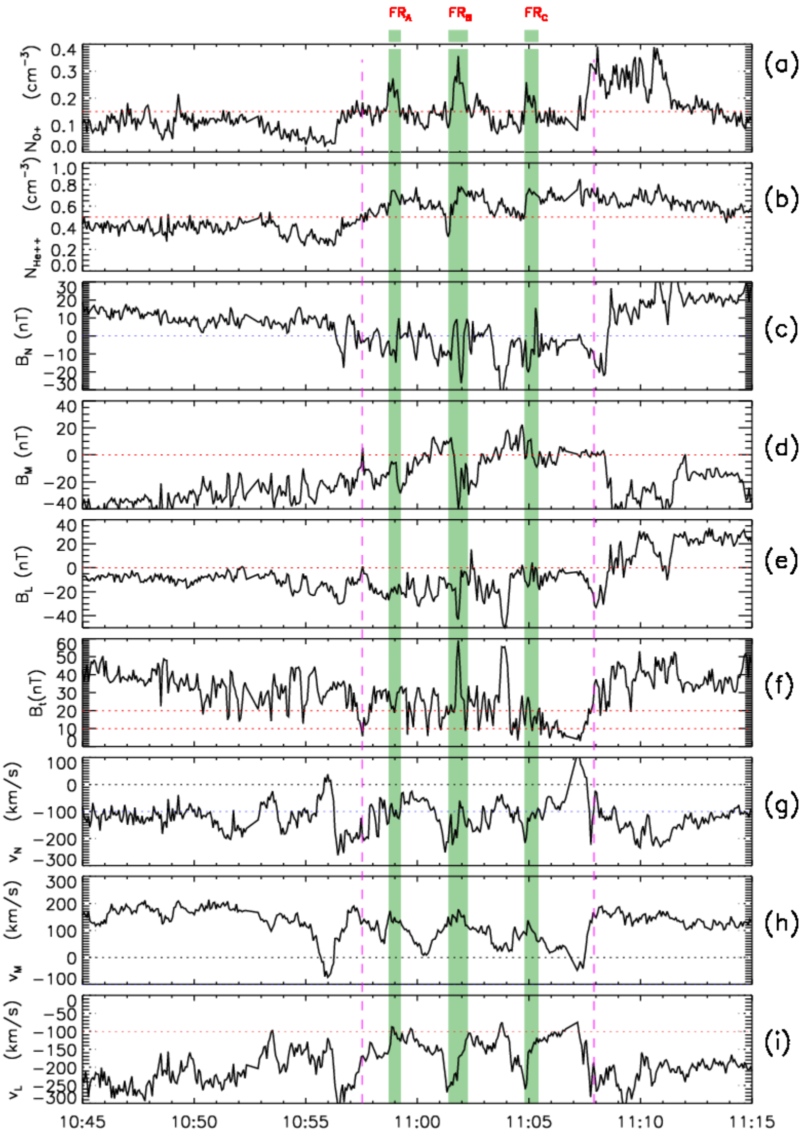

Figure 5 Sequential Flux ropes accumulated by energetic oxygen ions observed by Cluster C4 in southward high altitude cusp region, which are marked by FR_A, FR_B, FR_C at the top, respectively. From top to bottom, panels are (a) O^+ number density, (b) He^{++} number density, (c) the magnetic field B_N component, (d) the B_M component, (e) the B_L component, (f) the total magnitude B_t, (g) to (i) proton velocity v_N,v_M,v_L component, respectively. Three green shade regions mark the intervals of flux ropes and high number density of O^+ ions as FR_A, FR_B, FR_C at the topside of Figure 5, respectively.

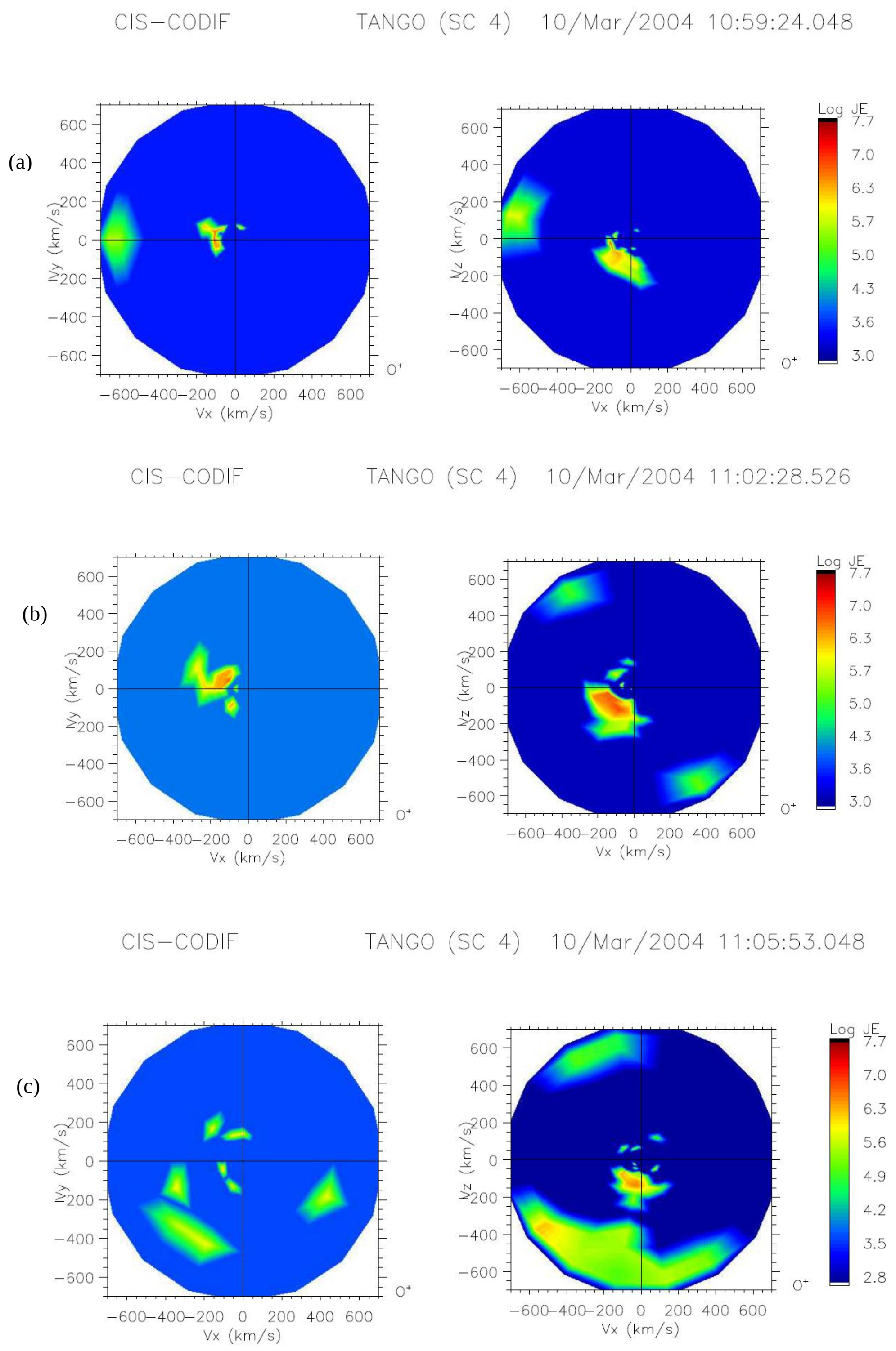

Figure 6 Two-dimensional cuts of the three-dimensional O^+ ion velocity distributions obtained by CODIF/C4 on 10 March 2004. Panels (a) to (c) show the O^+ ion velocity distributions in three flux ropes FR_A, FR_B, and FR_C at 10:59:24 UT, 11:02:28 UT, and 11:05:53 UT, respectively.