Evidence of O^+ ions energized by weak fast shocks in the mid-altitude cusp

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Key Points:

- Tens keV O^+ ions are detected by Cluster in the mid-altitude cusp.
- O^+ ions are efficiently energized in the perpendicular direction to the magnetic field by weak fast shocks in the mid-altitude cusp.
- Energetic O^+ ions in the mid-altitude cusp have bunch or partial ring distributions..

Abstract

Oxygen ions, O^+, efficiently energized by weak fast shock in the mid-altitude cusp observed by Cluster on 7 November 2004 are investigated in this paper. An interplanetary fast shock hitting Earth magnetosphere was observed by Geotail spacecraft at 1825 UT with a sharply increase in the solar wind dynamic pressure from 3nPa to 11nPa. There are significant fluctuations of solar wind dynamic pressure in the interval of 1930 UT to 2000 UT during this long time fast shock compressing Earth magnetosphere. During this pressure disturbance intervals Cluster 4 was located in the mid-altitude cusp, (0.43, -3.25, 3.07) R_{E_GSE}. CODIF/Cluster 4 instrument detected O^+ ions with tens keV energy energized by the weak fast shock with Mach number M_A~1.2 in the perpendicular direction. Those energetic O^+ ions associated with the weak fast shock have bunch or partial ring distributions in the mid-altitude cusp. Our observation results put forward confident evidences on the weak fast shock efficiently energizing heavy ions, especially, O^+ ions in the cusp.

Plain Language Summary

Singly charged oxygen ions, O^+, origin from the ionosphere with very low energy have low outflow speed. Usually, the energy of O^+ ions in the mid-altitude cusp is as low as ~300 eV. An energization mechanism for the low energy O^+ ions is needed for their outflow. The broadband low frequency waves (BBLFW) and ambipolar electric fields are the main mechanisms for O^+ ions outflow. But the mechanism energizing O^+ ions to tens keV still remains to be understood. In this report we present a new efficient mechanism for O^+ ions energizations. The weak fast shocks in the magnetosphere can energize O^+ ions to tens keV in the mid-altitude cusp.

1 Introduction

Oxygen ions, O^+, origin from the ionosphere, play a significant role in the magnetospheric dynamics during intense geomagnetic storms and substorms [e.g., Daglis, 2006; Duan et al., 2017; 2019; Fu et al., 2001; Kistler et al.,2016; Zeng et al., 2020]. The energy density of energetic O^+ ions can be a dominant component with larger than 50% of ring current during intense storms [e.g., Daglis and Axford, 1996; Fu et al., 2001]. The cusp is one of major source regions of O^+ ions which are distributing in the magnetospheric active regions, such as, plasma sheet and ring current [e.g., Kistler et al.,2016; Liao et al.2010; Yau et al.,1997; Yu and Ridley.,2013]. Previous studies reported that the energy of O^+ ions upflowing from the ionosphere was very low, ~ eV [e.g., Yau et al., 2007]. They can be energized to higher energy with escaping velocity and outflow into the higher altitude polar region [Andre et al., 1990; Yau et al., 2007]. O^+ ions can be transversely energized to tens and hundred eV in the mid-altitude cusp by the broadband low frequency waves (BBLFW) [e.g., Andre et al., 1990; Chang et al., 1986; Yau et al., 2007; Bouhram et al., 2004; Slapak et al.,2011].

Duan et al. [2019] reported that there were counter-stream O^+ ions with energy ~10s keV in sequential flux ropes in the high altitude cusp. They proposed that the mid-altitude cusp was one source region of these energetic O^+ ions in the high altitude cusp. While, O^+ ions in the mid-altitude cusp are usually with energy ~300 eV [e.g., Yau et al., 2007; Bouhram et al., 2004]. O^+ ions with energy ~10s keV in the mid-altitude cusp are rarely reported. The energization mechanism for these outflow O^+ ions with high energy in the mid-altitude cusp still remains to be solved.

Previous research work indicates that the weak fast perpendicular shock can efficiently accelerate ions, especially, heavy ions [e.g., Lee et al., 1986; Lee et al., 1987; Lee and Lee, 2016]. Simulation results of significant ion heating by quasi-perpendicular shock were first reported by Lee et al. [1987]. The accelerated ions show a ring or bunch velocity distribution in the downstream region of weak fast shocks [e.g., Lee et al., 1987; Lee and Lee, 2016]. Lee and Wu [2000] reported that the weak fast shock with $1.1 < M_A < 1.5$ can accelerate heavy ions, such as O^{5+}, to high speed ~460 km/s in the solar wind. Lee and Lee [2016] reported that the weak fast shocks in the magnetosphere were driven by the solar wind dynamic pressure enhancements or fast shocks in the solar wind through interaction with bow shock and magnetopause.

The mechanisms for O^+ ions energized up to 10s keV in the mid-altitude cusp is an interesting subject. This energization process still remains to be understood. Using conjunction observations of Geotail spacecraft in the dayside interplanetary space and Cluster in the mid-altitude cusp 7 on November 2004, demonstrate that the O^+ ions are energized from hundred eV to tens keV in the mid-altitude cusp by weak fast shocks associated with solar wind dynamic pressure increase. The detailed analysis is presented in sections 2 and 3. Discussion and summary are presented in section 4. The GSE coordinates are adopted in our paper.

2 Conjunction observations of weak fast shocks in the mid-altitude cusp

The solar wind density and velocity and interplanetary magnetic field (IMF) during an interplanetary shock on 7 November 2004 detected by Geotail spacecraft located around (19.0, 12.0,-5.0) R_E are presented in Figure 1. The solar wind number density and velocity are both very high, as shown in Figure 1a and Figure 1b, respectively. N_{ion} is in the range from 10 cm^{-3} to 30 cm^{-3}. The solar wind speed is around -650 km/s and remained for a long time interval ~2 hours. The solar wind dynamic pressure increased sharply from 5nPa to 10 nPa at 1827 UT as marked by the first vertical red dotted line in Figure 1c. At the same time, the magnetic field magnitude also increase from 23nT to 45nT as presented in Figure 1d. The B_z and B_y components both increase significantly, as shown in Figure 1e and 1f, respectively. The B_x component does not change clearly as presented in Figure 1g. The dominant component B_z increases from 20 nT to 38 nT as marked by the first vertical dotted line in Figure 1e. The solar wind dynamic pressure and magnetic field increase simultaneously, indicating that a perpendicular shock is detected. We calculate the shock normal angle ~80 degree and the Alfven Mach number of this shock, M_A~1.9, as the B_z component being tangent to the shock plane. The B_z and B_y component both retain mainly positive value for about 1 hour interval as shown in Figure 1e and 1f. These plasma and electromagnetic field characteristics indicate that the fast shock will compress the magnetosphere after 1827 UT. The high solar wind dynamic pressure maintained a large value for more than 1.5 hour, as shown in Figure 1c. It means that this fast shock lasted for a long time intervals. There are several significant fluctuations in the solar wind number density and magnetic field. At 1933UT, the solar wind dynamic pressure decrease sharply, from 25 nPa to 12 nPa, as marked by the second red vertical dotted line in Figure 1c. After this dynamic pressure decreased, the solar wind dynamic pressure increased significantly at 1937UT, 1941UT, 1945UT, as marked by three color shaded regions, as green, pink and blue in Figure 1c, respectively. Accompanied with these dynamic pressure enhancements the magnetic field B_t increases slightly, as shown in Figure 1d. These are significant signatures for weak fast shocks. During these weak fast shock the B_z component is dominant with large positive value ~40 nT, as displayed in Figure 1e. The B_y component is dominantly negative around ~ -20 nT, as presented in Figure1f. When these fast shocks passed through Earth magnetosphere their velocity slows down. The Mach number M_A is around 1.2. As mentioned by Zong et al. [2009] and Lee and Lee [2016], this weak fast shock played a significant role in the magnetosphere dynamic. Figure 2 shows the corresponding signatures of these weak fast shocks in the mid-altitude cusp observed by Cluster during 1930UT to 2000 UT.

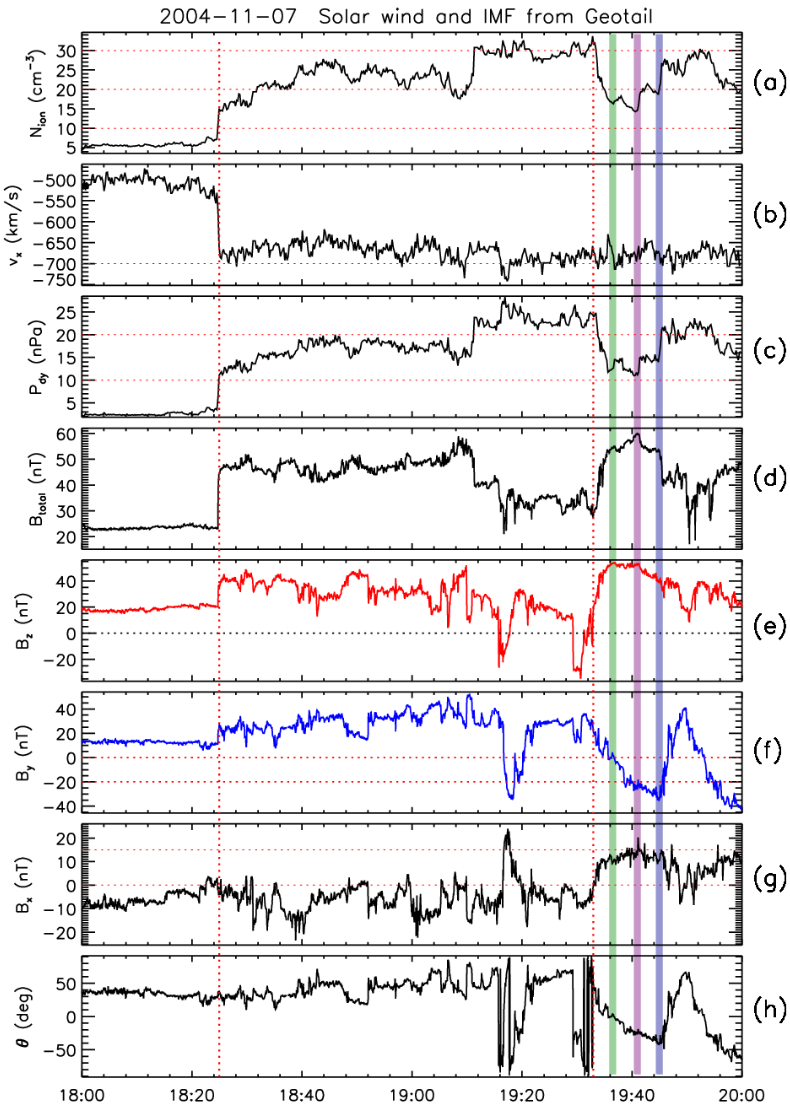

Figure 1. Solar wind plasma and IMF during a fast shock detected by Geotail on 7 November 2004 are displayed. From top to bottom, panels are (a) solar wind ions number density, N_{ion}, (cm^{-3}), (b) the x component velocity of ions, v_x, (km/s), (c) solar wind dynamic pressure, P_{dy}, (nPa), (d) the total magnitude of IMF, B_t, (nT), (e) IMF B_z, (f) IMF B_y, (g) IMF B_x ,(h) the IMF clock angle, θ=arctan(B_y/B_z), respectively.

As the reaction of the solar wind dynamic pressure decreased significantly from 25nPa to 10nPa at 1933UT in Figure 1c, the Earth magnetosphere expanded outward. Thus Cluster C4 located at the northern hemisphere (0.55,-3.33, 2.90) R_E encountered the cusp. The high number density of ions and electrons were detected by Cluster C4; both increased sharply at 193530UT, as marked by the first red vertical dashed line in Figure 2a. Between two red vertical dashed lines, the number density of He^{++} is high, larger than 0.5 cm^{-3} as shown in Figure 2b. The x component of proton velocity is low with 50km/s fluctuations as presented in Figure 2e. The magnetic field has significant fluctuations in three components as shown in the bottom three panels, Figures 2g to 2i. These plasma and magnetic field features are consistent with the characteristics in the mid-altitude cusp [e.g., Guo et al., 2008; Duan et al., 2006]. With ~3 min lag for time shift from Geotail location to Cluster/SC4 location, the weak fast shocks play significant role in O^+ ions energization in the mid-altitude cusp. Three color shade regions in Figure 2 are corresponding three weak fast shocks observed by Geotail in dayside solar wind space with one-to-one relationship, respectively. As shown in Figures 2a to 2c and Figures 2g to 2i, in these three shade regions, electrons and ions density and the magnetic field significantly increase. The B_y is the dominant component of the magnetic field during these three intervals. For simplicity we assume the y component as the field tangential to the shock normal plane. Using the method reported by Lee and Lee [2016], we calculate the upstream angle between the background magnetic field and shock normal θ_{BN} = 54 degree, and the Alfven Mach number M_A=1.11. Within these regions, the number density of O^+ ions increases significantly, from 2 cm^{-3} to 4 cm^{-3}, as shown in Figure 2c. The electric field is very large, ~ 10s mV/m, and especially, in the first shade regions, the E_x component approaches to 40 mV/m as presented in Figure 2f. These weak fast shocks are accompanied with a significant large electric field E_x in the perpendicular direction to the magnetic field and they are associated with a significant increase of O^+ ions number density in the mid-altitude cusp.

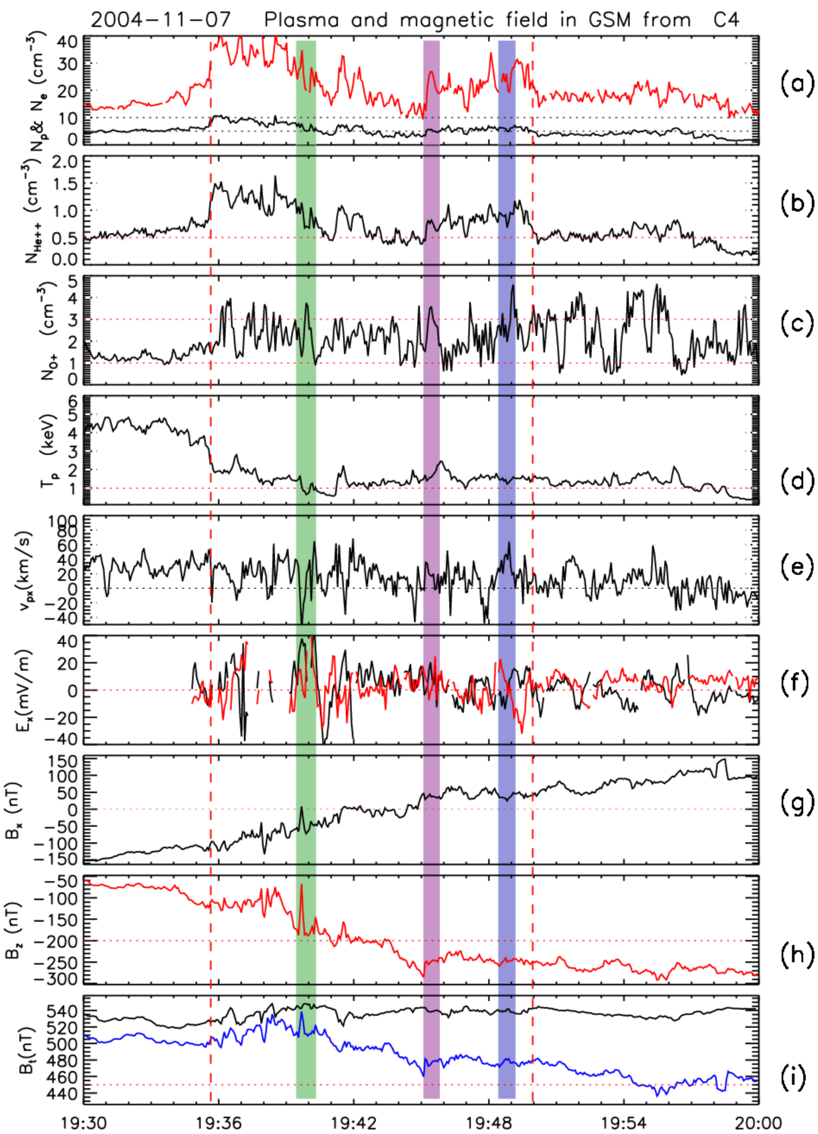

Figure 2. Plasma and electromagnetic field in the mid-altitude cusp observed by Cluster/SC4 on 7 November 2004. From top to bottom, the panels are (a) proton and electron number density, N_p (black), N_e (red), (cm^{-3}), (b) Helium number density, N_{He++},(cm^{-3}), (c) O+ ion number density, N_{O+} , (cm^{-3}), (d) Proton temperature T_p (keV), (e) X component of proton velocity, v_{px}, (km/s), (f) the X and Z components of the electric field, E_x (black), E_z(red) (mV/m), (g) B_x (nT), (h) B_z, (i) B_t (black) and By(blue), respectively.

3 Evidence of O^+ energized by weak fast shocks in the mid-altitude cusp

The energy flux and pitch angle distributions of O^+ ions obtained from CODIF/CIS instrument [Reme et al., 2001] onboard Cluster/SC4 in the mid-altitude cusp in the intervals from 1935UT to 1955UT on 7 November 2004 are presented in Figure 3. During the intervals from 1936 UT to 1950 UT Cluster C4 is located in the northward hemisphere mid-altitude cusp. Thus, the O^+ ions pitch angle is within a large degree range, from 135 degree to 180 degree, indicating that these oxygen ions are outflow from the cusp region, as shown in Figure 3b. These O^+ ions are mainly with low energy less than 1keV. But the pitch angle of O^+ ions with higher energy larger than10 keV shows significant flux increase around ~90 degree, i.e., in the range of 45 degree to 135 degree, especially, at 1940 UT, 1945 UT, and 194830UT as marked by three black vertical lines in Figure 3d, respectively. These three times are all within the time intervals corresponding to three color shade regions assigned as green, pink and blue in Figure 2, respectively. The pitch angle around 90 degree means energetic O^+ ions are distributed dominantly in quasi-perpendicular direction to the magnetic field. In order to show more features of these high energy O^+ ions, we will present the detailed oxygen ions velocity distributions in the vicinity of these three times.

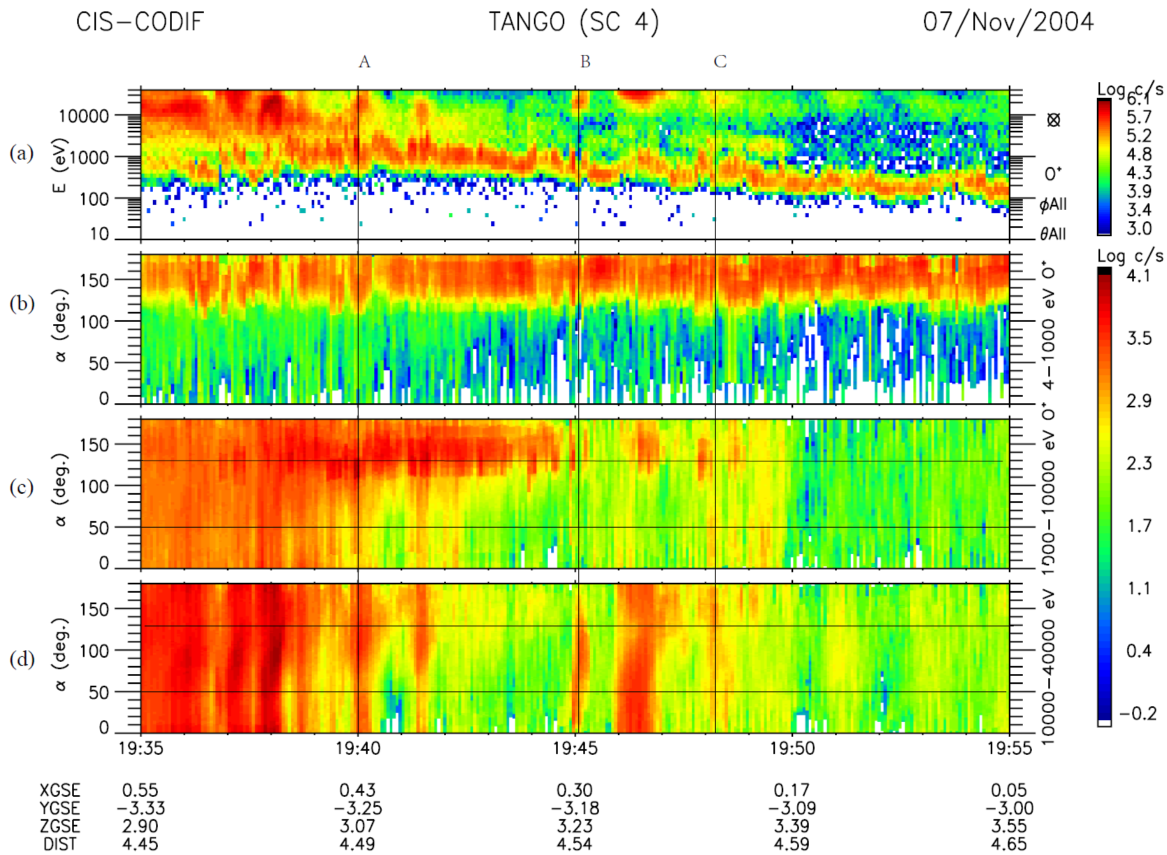

Figure 3. Energetic oxygen ions energy flux and pitch angle distributions observed in the mid-altitude cusp regime. (a) O^+ ions energy flux, (b) to (d) the pitch angle of O^+ ions with energy range (4 to 1000eV), (1keV-10keV) and (10keV-40keV), respectively. The vertical lines assigned as A,B,C marked the time of O^+ ions energy flux sharply enhancement with quasi-perpendicular pitch angle in the high energy range around 1940 UT, 1945UT, and 194830UT, respectively, which correspond to the three shaded color regions in Figure 2.

Figure 4 presents the O^+ ions velocity distributions at 194015 UT, 194516 UT, and 194835 UT, respectively. These three times are marked by three black vertical lines assigned as ‘A’,’B’,and

'C' in Figure 3. Energetic O^+ ions with tens keV energy at these three times are dominant in the quasi-perpendicular direction with pitch angle in the range 45 degree to 135 degree, as shown in Figure 3d. At these three times, energetic O^+ ions velocity distributions, displayed in Figure 4a to 4c, respectively, have bunch or partial ring distributions. O^+ ions are energized by the weak fast shocks with intense perpendicular electric field (E_x), as shown in Figure 2f with three color shade regions. They are all associated with the solar wind dynamic pressure increases assigned as three shaded color regions in Figure 1c. These observational energetic O^+ ions having bunch or partial ring distributions are consistent with the simulation results reported by Lee et al [1987]. They proposed that ions can be energized by the weak fast shock in the perpendicular directions to the background magnetic field. Our observation results present that O^+ ions accelerations are associated with the significant intense electric field in the weak fast shock structures. As shown in Figure 2f the electric fields have significant enhancements with large-amplitude fluctuations, the maximum value is E_x ~40 mV/m.

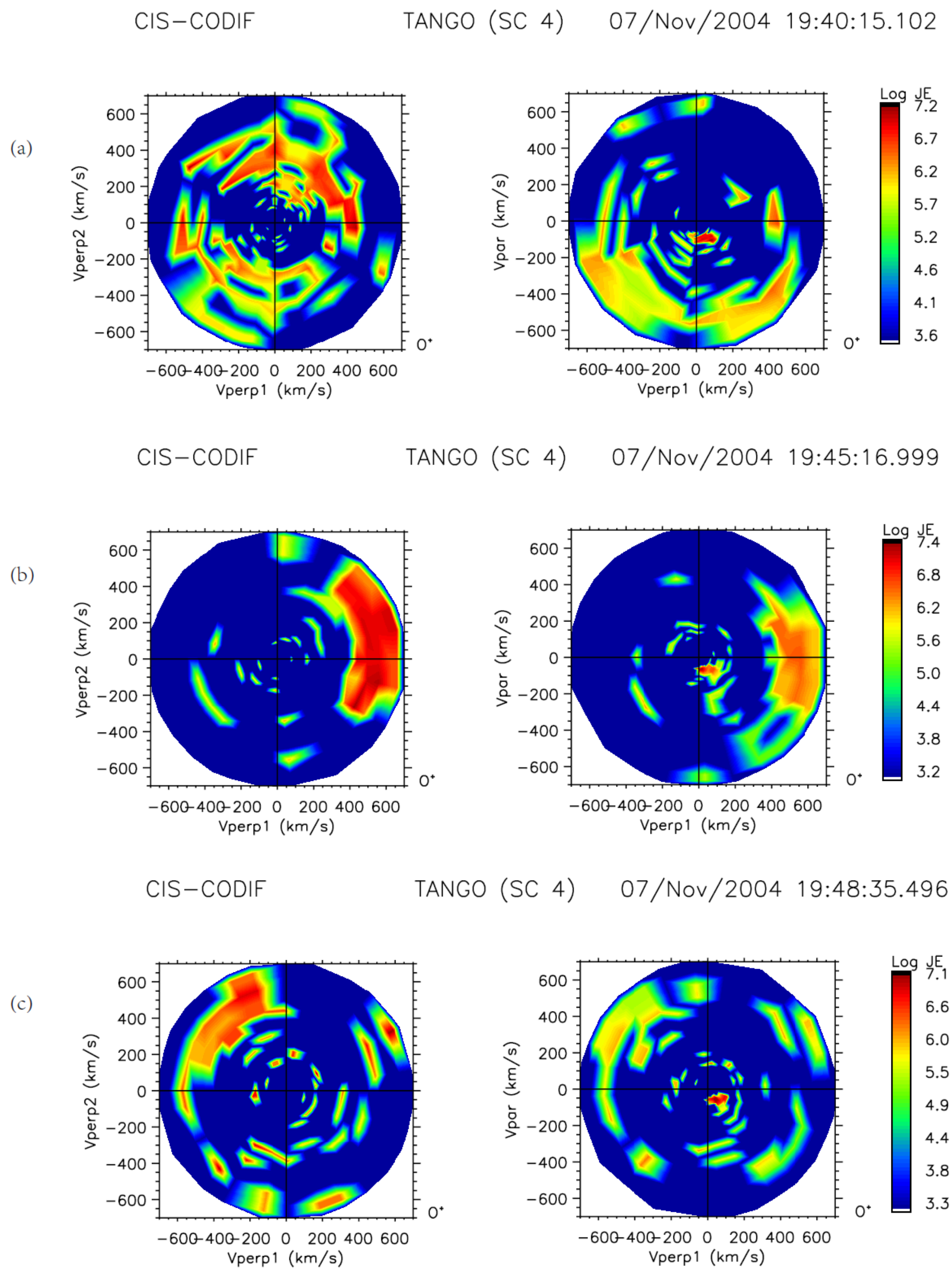

Figure 4. Two–dimensional cuts of the three-dimensional O^+ ions velocity distributions obtained by CODIF/C4 in the mid-altitude cusp at 194015 UT, 194516 UT, and 194835UT, respectively.

4 Discussion and Summary

As mentioned above when Cluster/SC4 crossing the mid-altitude cusp in dawnside during the intervals from1935 UT to 1950 UT on 7 November 2004, the IMF B_z component is positive with a large value from 20 nT to 50 nT. The IMF B_y component is negative with ~ - 20 nT. Thus, this large positive B_z component implies that there is no effect of dayside magnetic reconnection on the cusp during this period. On the other hand, under this IMF condition the cusp location shifts to the dawnward. Pitout et al [2006] reported that during the northward IMF the location of the cusp depending primarily upon the solar dynamic pressure and the Y-component of IMF. Figure 1c shows that the solar wind dynamic pressure has three step enhancements from 10 nPa to 23 nPa at 1937 UT, 1941 UT and 1945 UT. Under this large solar wind dynamic pressure, the cusp spatial scale can expand to a larger size. Thus the solar wind dynamic pressure dominantly controls the cusp location during this interval.

Lee and Lee [2016] proposed that weak fast shocks can be driven by the solar wind dynamic pressure enhancements. Figure 3a displays significant enhancements of tens keV O^+ ions energy flux spectrum at 1940 UT, 1945 UT and 1948 UT. These enhancements are associated with the solar wind dynamic pressure increases in Figure 1c at 1937 UT, 1941 UT and 1945 UT, respectively. The corresponding energetic O^+ ions pitch angle distributions as shown in Figure 3d have significant quasi-perpendicular signatures. These associated observations imply that the three weak fast shocks accelerated O^+ ions in the perpendicular direction to the magnetic field.

A thin ramp with spatial scale smaller than ion inertial length is a significant property for a quasi-perpendicular shock [e.g., Leroy et al., 1982; Lee et al., 1986]. The weak fast shocks are accompanied with a significant perpendicular electric field as addressed by Lee and Wu [1990], especially, through the shock ramps. Figure 2f shows that there really are significant perpendicular electric fields, E_x, associated with these weak fast shocks detected by Cluster/SC4 in the mid-altitude cusp. Within shock ramp the perpendicular electric field with large amplitude can efficiently accelerate O^+ ions. As shown in three color shade regions in Figure 2f, the X component of the electric field has a large amplitude, E_x ~ 40mV/m, 10mV/m and 20mV/m, respectively. These three large perpendicular electric fields in the shock ramp with spatial scale 100km are corresponding to quasi-perpendicular pitch angle of energetic O^+ ions with energy tens keV as marked by three vertical black lines, respectively, in Figure 3a and 3d.

Lee and Wu [2000] proposed that the weak fast shock could energize heavy ions in the direction perpendicular to background magnetic field leading to a bunch or partial ring velocity distribution. Our investigations on these energized O^+ ions velocity distributions at three time 194015UT,194516UT and 194835UT display bunch or partial ring distribution as shown in Figure 4a,4b and 4c, respectively. It demonstrates that our observation results provide confident evidences for previous theory and simulation results [e.g., Lee et al., 1986; Lee et al., 1987; Lee and Wu 2000; Lin et al., 2004].

Tens of keV O^+ ions in the mid-altitude cusp associated with weak fast shocks are observed by Cluster/SC4. These energetic O^+ ions can outflow into the high-altitude cusp. Duan et al [2019] reported that energetic O^+ ions with energy ~ tens keV in the high-altitude cusp have counter-streaming distributions. They suggested that the mid-altitude cusp was one source region of these energetic O^+ ions. Our studies provide confident evidences that O^+ ions can be efficiently energized by weak fast shock to tens keV in the mid-altitude cusp. These energetic O^+ ions may flow outward into high-altitude cusp.

Based on conjunction observations between Geotail in the solar wind and Cluster in the mid-altitude cusp on 7 November 2004, we propose a new mechanism for O^+ ions, which are efficiently energized by weak fast shock to tens keV in the mid-altitude cusp. These energetic O^+ ions present bunch or partial ring distribution in the mid-altitude cusp. Our observations results provide some confident evidences that the weak fast shock can efficiently energize heavy ions, especially, O^+ ions in the cusp region.

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