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Investigation of the source region of ionospheric oxygen outflow in the cleft/cusp using multi-spacecraft observations by CIS onboard Cluster

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Abstract

Beams of singly ionized oxygen with narrow energy distributions originating in the dayside cleft/cusp region are frequently observed in the cleft, cusp and polar cap regions by the CODIF sensor of the CIS instrument onboard Cluster. During summer and fall of 2001, the high separation distances of $\sim 1Re$ between the spacecraft provided a good opportunity to estimate the size and location of the source of outgoing O^+ ions. A statistical study shows that the source region is located near the equatorward edge of the cleft/cusp region, within a latitudinal range of around 1.5°. The longitudinal extension cannot be resolved, except that it is more than the satellite separations that was 14° in average. Cluster observations inside the source region, at 4.5–6*Re*, show high transverse heating of the O^+ population. This process is accompanied with a sudden enhancement of low-frequency electric field waves measured by the EFW and STAFF instruments. We suggest that O^+ ion outflow is caused by resonant heating by BBELF waves.

Keywords: Ionospheric oxygen; Cluster; Cleft/cusp; Multi-spacecraft observations

1. Introduction

The outflow of low-energy O^+ ions from the cusp/cleft region was discovered two decades ago by the DE 1 satellite (Lockwood et al., 1985a); Moore et al. (1986) named these flows "upwelling ions" and Lockwood et al. (1985b) called this outflow "cleft ion fountain". It was suggested that the suprathermal O^+ outflow observed at 2000–5000-km altitudes is the source of the field-aligned higher altitude spatially dispersed cusp and polar cap oxygen outflows (Moore et al., 1986, and references therein). Upward moving O^+ ions in the cleft/cusp and polar cap region have been extensively studied

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using data from different satellites (e.g., Valek et al., 2002), and it was shown that cleft/cusp originating outflow is one of the major sources of the magnetospheric heavy ion populations (see reviews by Andre and Yau, 1997; Moore et al., 1999), but properties of the outflow and source region are still under discussion. Moore et al. (1986), Dubouloz et al. (2001, 1998), and Bouhram et al. (2002) found that the source region of this outflow is located inside the dayside cleft/cusp region, and Andre et al. (1990) showed that the source region is placed near the equatorward edge of the cleft/cusp. Previous detailed studies showed (see review by Moore et al., 1999) that O^+ outflow is caused by the resonant heating by broadband extra low-frequency electric field waves (BBELF turbulence), such as long wavelength Alfven waves, ion acoustic waves and electrostatic ion cyclotron waves, or/and electromagnetic ion cyclotron waves. The contributions of the different waves to the acceleration process is still under discussion (Bouhram et al., 2002). The altitude location of the heating region was found to vary from 2000 km (Moore et al., 1986) to 15,000 km (Dubouloz et al., 2001). Dubouloz et al. (1998) and Bouhram et al. (2002) showed that the ion acceleration in the directions perpendicular to the magnetic field occurs at all altitudes extending up to 15,000 km. While many studies (Lockwood et al., 1985b; Andre et al., 1990; Dubouloz et al., 1998) have shown that a typical latitudinal width of the acceleration region is 1.5–2°, Dubouloz et al. (2001) presented a case study for a wider source region, 5°. Lockwood et al. (1985a) showed that the O^+ outgoing ions permanently exist in the cleft/cusp region, but the location of the source is variable with time, and it was shown that the source region extends in the longitude direction (Bouhram et al., 2002).

During summer and autumn 2001, the Cluster satellite orbits provided the opportunity to study ion populations in the mid-altitude cleft/cusp region: the spacecraft crossed the north and south cusps twice per orbit in a "string of pearls" configuration, and the separation distance between spacecraft was high, 0.5–2*Re*. In 80% of all cusp crossings we have observed oxygen ion outflow from the cusp region. In this paper we study the common features of these outflow events and estimate the location and size of the outflow source region.

We used ion data from the time-of flight ion COmposition and DIstribution Function (CODIF) sensor experiment (Rème et al., 2001), which combines a top-hat analyser with an instantaneous 360° field of view with a time-of-flight section to measure complete 3D distribution functions of the major ion species, H^+, He^{++}, He^+, and O^+. The sensor covers the energy range between 0.02 and 38 keV/q.

In our study, we have also used information on low-frequency electric field fluctuations obtained by two Cluster wave experiments: the Electric Field and Wave (EFW) experiment (Gustafsson et al., 1997) and the Spatio-Temporal Analysis of Field Fluctuations (STAFF) experiment (Cornilleau et al., 1997).

2. Observation and discussion

For our study we have selected 10 events, five from each hemisphere (see Table 1) with a clear signature of O^+ outflow. These events occurred during both quiet times or times with moderate geomagnetic activity (see *Kp* index in Table 1 as indicator of geomagnetic activity). The Cluster satellites during these events had similar orbits around perigee: dayside inner magnetosphere, cleft, cusp, polar cap in the North and polar cap, cusp, cleft, dayside inner magnetosphere in the South. The selected oxygen outflow events exhibit several common features: (1) the O^+ outflow has a very narrow energy range, indicating that the whole population was accelerated to the same bulk velocity, which is typical for the upwelling ions (Moore et al., 1999); (2) O^+ outflow begins at the equatorward edge of the cleft/cusp region, followed by an enhancement of energy and upward velocity of the O^+ ions to a maximum value; (3) after this, in the cusp and polar cap regions, there exists a long-lived O^+ beam with a gradual decline of energy and upward velocity.

Fig. 1 shows an example of such an O^+ outflow seen on S/C 4 the 23rd of August 2001, 12:40–13:10 UT. The top and middle panels display energy–time spectrograms of H^+ and O^+ ions, respectively. Protons exhibit a typical cusp feature, i.e., an energy–time dispersion that can be explained by different travel times from the reconnection point for ions with different energies (Smith and Lockwood, 1996). Oxygen data show a beam-like signature as described above. The bottom panel presents parallel velocities of the H^+ (grey) and O^+ (black) populations, where positive values are for downward-moving (precipitating) ions. Oxygen outflow starts approximately at 12:46 UT, followed by a sharp increase of the parallel outflow velocity until 12:48 UT. During this time interval the S/C crossed narrow acceleration region in latitudinal direction (two dashed lines in Fig. 1 mark the equatorward and poleward boundaries of this region) . After 12:49 UT the satellite exits the acceleration region and the parallel velocity gradually decreases. The energy dispersion of the O^+ ions observed in the cusp and polar cap can be explained as a time-of-flight effect of the oxygen ions from acceleration region to the observation point under the action of the $E \times B$ convection (Lockwood et al., 1985b). Proton data show that at 12:46 UT H^+ ions started to be accelerated upward together with oxygen ions, and only at 12:48 UT there is the first strong downward injection of protons, and a second one at 12:50 UT.

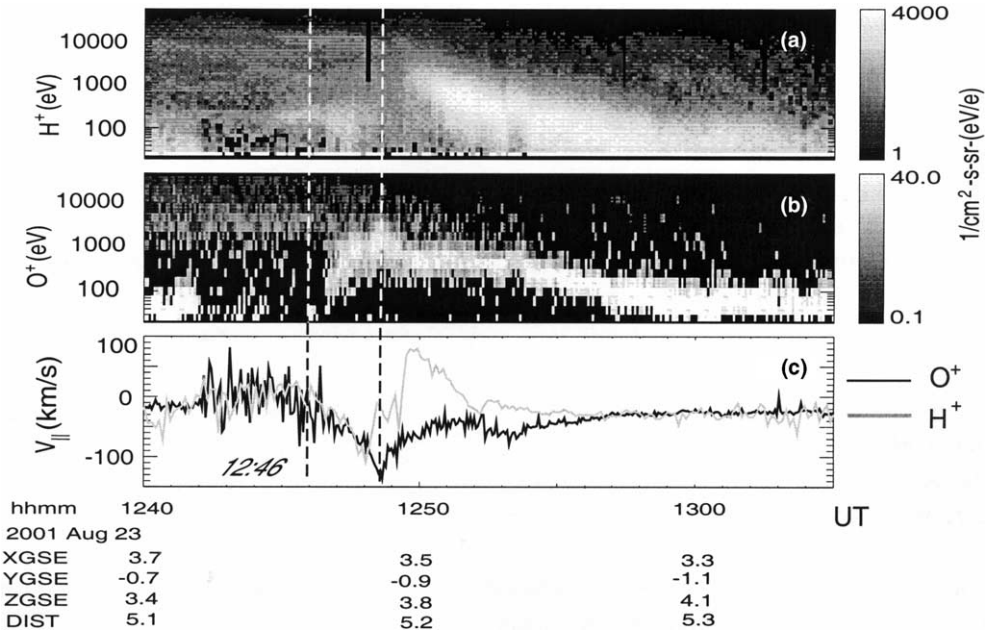

Fig. 1. CIS data for August 2001 event, from S/C 4: energy–time spectrograms of H^+ (a) and O^+ (b) populations and parallel velocity of ions (c), H^+ (grey) and O^+ (black). First dashed line at 12:46 UT marks the start of the oxygen outflow, this happens 3 min before the first proton injection. Second dashed line marks point with maximal outflow energy and parallel velocity of O^+ ions (poleward boundary of the acceleration region).

These observations prove that the source of the upward moving ions is located near the equatorward edge of the cleft/cusp, partially before first magnetosheath proton injection.

For understanding of the processes responsible for the ion acceleration and outflow, we have studied the O^+ distribution function throughout the cleft and cusp crossing. The left panel of Fig. 2 shows the O^+ velocity distribution function at 12:47:32–12:48:00 UT when Cluster satellite was inside the acceleration region. The distribution function shows very high perpendicular heating: O^+ perpendicular velocity distribution is very wide with a full-width-half-maximum of 100–120 km/s. The right panel presents the O^+ distribution function at 12:55:00–12:55:30 UT, and one can see that the ion distribution is now different: oxygen ions appear as a beam and this feature continues to exist during the cusp crossing.

Fig. 3 presents data from the EFW (panel a) and STAFF spectrum analyser (panel b) experiments for the same time interval. The first and second panels show the electric field power spectral density in the spin plane in the frequency band 1–10 and 10–180 Hz, respectively. Both values can be used as indicators of the activity of

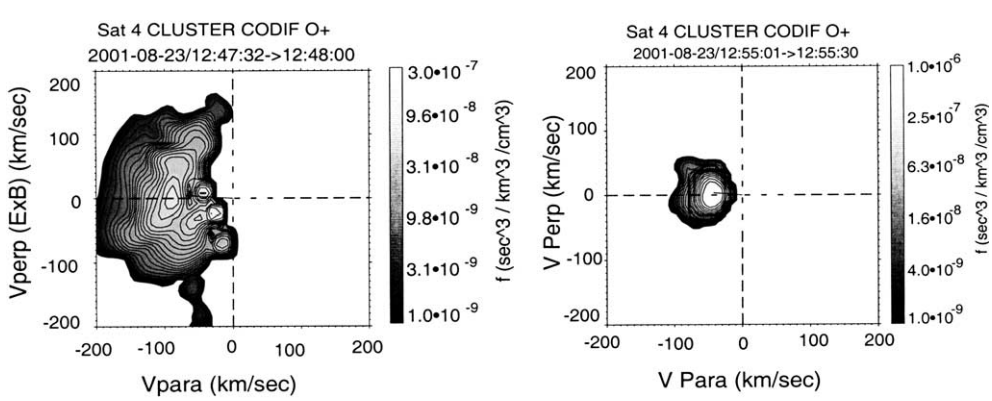

Fig. 2. On 23 August 2001, two oxygen distribution functions from Cluster 4 in a plane ($V_\parallel$, $V_\perp$). The distributions are averaged over 30 s and contain the bulk velocity. $V_\parallel$ is aligned with the local magnetic field, and $V_\perp$ is in the $-(V \times B) \times B$-direction. Twenty levels of contours of differential energy flux are evenly spaced logarithmically between the minimum and maximum values. The left panel shows O^+ distribution function with high perpendicular component which is typical for transverse heating mechanism. Eight minutes later (right panel) oxygen ions exhibit a beam-like behaviour.

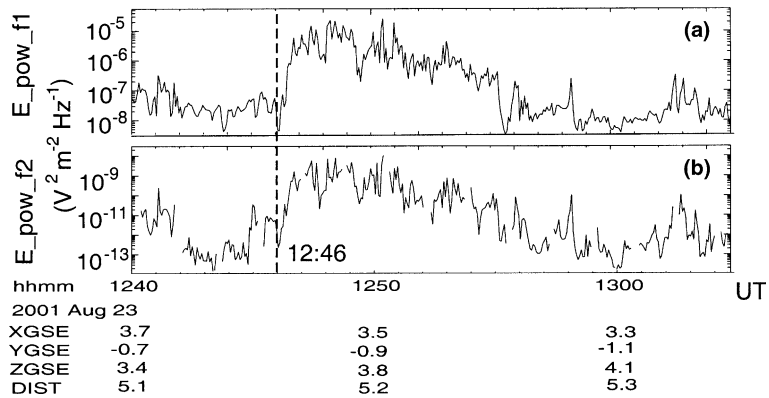

Fig. 3. EFW and STAFF power spectral densities from Cluster 4 on 23 August 2001 in the spin plane in the frequency bands 1–10 Hz (a) and 10–180 Hz (b). Dashed line at 12:46 UT marks time of the beginning of the sharp enhancement of the wave activity.

low-frequency electric field waves. At 12:46 UT (dashed line), we observe a sharp enhancement of the electric field power spectral density in both frequency bands by 2–3 orders of magnitude, indicating that the Cluster S/C is in the region with high low-frequency electric field turbulence. The onset of transverse heating and outflow of O^+ ions coincides with the sharp increase of the low-frequency waves, and we conclude that oxygen ions acceleration is caused by resonant energization by the BBELF waves at 5*Re* during this event.

3. Statistics and model results

For a statistical study of the location and size of the source region of the upward moving O^+ ions, we have selected 10 events, five from each hemisphere (see Table 1). During these events, the satellite passed the acceleration region from onset, which we defined at the time of the start of O^+ outflow (equatorward boundary), to the end, which we marked as the point with maximal outflow energy and upward velocity (poleward boundary). Using these two points, we can estimate the latitudinal and longitudinal size of the acceleration region based on the data from one spacecraft. The third column in Table 1 shows which spacecraft was used and the fourth column contains two times for each spacecraft and each event: the time of the beginning of the O^+ outflow, marked as "start" and the time with the maximal upward velocity of the outflow, named as "end".

To estimate the latitudinal and longitudinal size of the source region, we used the Tsyganenko T96 magnetic field model (Tsyganenko, 1995) for the tracing of the "start" and "end" points described before to the ionosphere level (100 km). Model T96 has four input parameters, IMF B_z, IMF B_y, solar wind dynamic pressure and *Dst*-index. We have determined solar wind and IMF condition for each event using data from WIND or ACE spacecraft, correcting for propagation times.

The results of the mapping based on the T96 model are included in Table 1: geomagnetic latitudes of the equatorward and northward boundaries of the acceleration region (column five), geomagnetic longitudes of the eastward and westward edges of this region (column six), latitudinal (column seven) and longitudinal (column eight) sizes of the source region. The latitudinal size we have obtained from each S/C as a difference between latitudes of the "start" and "end" points, and the longitudinal size we have estimated as the maximum difference between longitudes of these points observed at all three spacecraft. These data show that the latitude of the source is variable and it is in the range 68.2–81.9° geomagnetic latitude. During each event latitudinal locations of the source region derived from different spacecraft are similar in spite of S/C 3 crossing this region usually around 30 min later than S/C 1 and 4. Based on all events, we estimated the latitudinal size of the acceleration region as ~1.5°. The longitude of the source region also varies from event to event. The O^+ outflow is observed at all MLT with the source longitude of S/C 3 showing differences of ~7–27° from the source longitudes derived from S/C 1 and 4 (corresponding to 0.5–1.8 h in MLT). Because the systematic differences of the source longitude of S/C 3 are due to the orbital configuration (see Table 1), and the long duration of O^+ outflow in the polar cap region of up to ~2 h, the source longitude difference is most likely due to the longitude extension of the source and not due to a source moving in longitude. Statistical study shows that the acceleration region extends at least 14° in longitude on average. We did not include effect of the $E \times B$ convection in the mapping procedure as we mapped points inside the heating region closed to the source and can neglect the convection as first approximation. Including convection in the mapping procedure will give us slightly different result mainly in estimation of the latitude.

Table 1
Model T96 results for 10 events

Date	*Kp*	S/C	Time of start/end	GM latitude of start/end	GM longitude of start/end	Latitudinal size	Longitudinal size
2 July 2001	1+	1	03:48–03:56	71.19/72.19	240.43/237.06	1.0	12.47
	1+	4	03:45–03:50	71.56/72.33	240.48/238.06	0.77	
	1+	3	04:27–04:34	70.13/71.14	230.59/227.96	1.01	
30 July 2001	2−	1	17:00–17:05	76.30/77.23	34.06/32.34	0.93	16.43
	2−	4	16:59–17:01	76.90/77.30	35.44/34.37	0.4	
	2−	3	17:36–17:38	75.52/75.76	19.01/19.06	0.24	
4 August 2001	1+	1	11:40–11:46	72.77/73.89	135.31/136.24	1.12	10.27
	1+	4	11:35–11:39	72.63/73.47	137.01/137.46	0.84	
	2−	3	12:13–12:18	73.17/74.15	127.19/127.99	0.98	
23 August 2001	2−	1	12:50–12:57	79.03/80.31	102.45/103.52	1.28	16.78
	2−	4	12:46–12:49	79.17/79.72	105.58/106.14	0.55	
	2−	3	13:21–13:29	79.09/80.60	89.36/90.30	1.51	
28 September 2001	3−	1	05:46–05:52	69.47/70.58	158.64/158.60	1.11	6.87
	3−	4	05:47–05:51	70.66/71.47	159.68/159.82	0.81	
	4−	3	06:18–06:21	69.26/69.87	152.95/153.03	0.61	
16 July 2001	2−	1	07:44–07:37	−68.23/−69.49	193.11/195.76	1.26	12.78
	2−	4	07:51–07:44	−68.47/−69.72	191.28/194.03	1.25	
	2−	3	08:27–08.24	−68.81/−69.42	182.98/184.00	0.61	
28 September 2001	3−	1	02:22–02:11	−70.50/−72.11	201.86/205.78	1.61	9.49
	3−	4	02:28–02:21	−71.34/−72.53	200.98/203.72	1.19	
	3−	3	02:54–02:45	−72.92/−74:25	196.29/200.33	1.33	
30 September 2001	2−	1	10:50–10:40	−81.98/−83.43	51.80/59.72	1.45	27.48
	2−	4	11:05–10:56	−81.61/−83.14	42.82/49.25	1.53	
	2−	3	11:34–11:15	−81.65/−84.52	32.24/42.64	2.87	
19 October 2001	3−	1	12:12–12:02	−76.62/−78.11	1.17/0.72	1.49	12.36
	3−	4	12:19–12:11	−76.84/−78.24	357.31/357.10	1.4	
	3−	3	12:52–12:46	−76.03/−77.06	348.81/349.01	1.03	
14 November 2001	0+	1	16:14–15:45	−73.55/−77.68	287.69/291.75	4.13	11.41
	0+	4	16:23–15:57	−74.20/−78.09	286.38/289.49	3.89	
	0+	3	16:57–16:45	−73.92/−75.67	280.34/282.72	1.75	

4. Conclusions

This paper presents a study of the upward moving O^+ ions observed by the Cluster CIS instrument in the mid-altitude cleft/cusp and polar cap regions during summer/fall 2001. Our investigation shows that the source of these ions is located near the equatorward boundary of the cleft/cusp and ions outflow sometimes begin before magnetosheath proton injections. A statistical study of 10 events shows that the source is localized in latitude, 1.5°, and can extend in longitude up to 27° (this was the largest satellite separation), corresponding to 1.8 h in MLT, with an average value of ~14° . Inside the source region CIS data show high perpendicular heating of the O^+ ions at an altitude of 4.5–6*Re*. Taken into account the observation of the sharp enhancement of the low-frequency electric wave fields in the same region, we conclude that transverse heating of O^+ ions is caused by resonant energization by broadband low-frequency waves. Based on the previous studies (Dubouloz et al., 1998; Bouhram et al., 2002), we suggest that the acceleration region can extend along magnetic field lines from 1700 km (FAST data) to high altitudes of 4.5–6*Re* crossed by Cluster during the events discussed in this paper.

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