The Relationship between O^+ Outflow and Sawtooth Events for ICME Storms

N Nowrouzi[1], E J Lund[1,2], L M Kistler[1], C Mouikis[1], X Cai, [3], H U Frey[4]
[1]University of New Hampshire, [2]College Brook Scientific, [3]Virginia Tech, [4] University of California, Berkeley

Introduction and Motivation

A series of papers [Brambles et al. 2011, Ouellette et al. 2013, Brambles et al., 2013] investigated the role of O^+ outflow in driving sawtooth events using the multiflued LFM model, and have proposed that O^+ outflow is a driver of the sawtooth mode. [**Brambles et al. 2011]** showed that for a steady solar wind driver, outflow caused the sawtooth events through a feedback mechanism. The first tooth is triggered by a southward turning. But after that, the energy driven into the auroral regions during the expansion phase drives more outflow. **Figure 1,** from [**Ouellette et al. 2013],** using the same simulation, shows that each expansion phase drives outflow, which then loads the plasma sheet. After a substorm, "**the nightside ionospheric outflow continues to fill the inner magnetosphere, stretching the field lines once again, resulting in another substorm**."

In addition, "**this stretching originates from the additional pressure of the magnetospheric O^+ population, which enhances both the "ballooning" pressure force and the diamagnetic ring current that shears the ambient magnetic field. "**

[**Brambles et al. 2013]** investigated two storms with sawtooth events, one driven by an SIR and one by a CME storms. They found that the CME storms behave like the earlier "steady solar wind" simulations, with the feedback mechanism driving nightside outflow.

SIR storms tend to drive more cusp outflow, and the sawteeth are directly driven. **Thus a fundamental difference between the two types of sawtooth events in the model is that CME events are driven by nightside outflow, while SIR events have more cusp outflow,** as shown in **Figure2a and 2b**.

Here, we use ACE, Cluster, LANL, IMAGE and FAST data to investigate one CME storm to determine if it follows the [Brambles et al. 2011] feedback mechanism. We will investigate the following predictions of the [Brambles et al.2011]:

1) Does the O^+ in the magnetotail during each sawtooth have signatures of nightside outflow or does it come from the cusp? The feedback mechanism drives nightside outflow.
2) Is there evidence of increased O^+ pressure during the growth phase of each tooth?
3) Is there evidence for strong outflow after each expansion phase and during the growth phase?

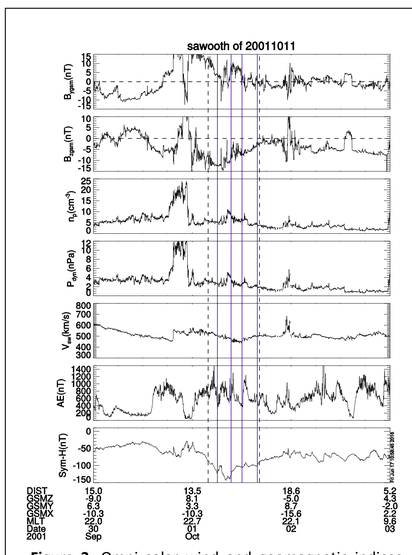

Figure 3. Omni solar wind and geomagnetic indices during the Oct 1, 2001 storm. Dashed black lines marked the time period of event and blue lines show the injection time.

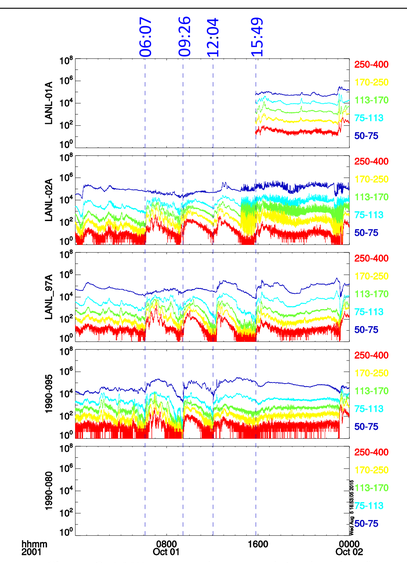

Figure 3. LANL geosynchronous data showing four sawtooth injections during the event. Injection time is marked by dashed blue lines.

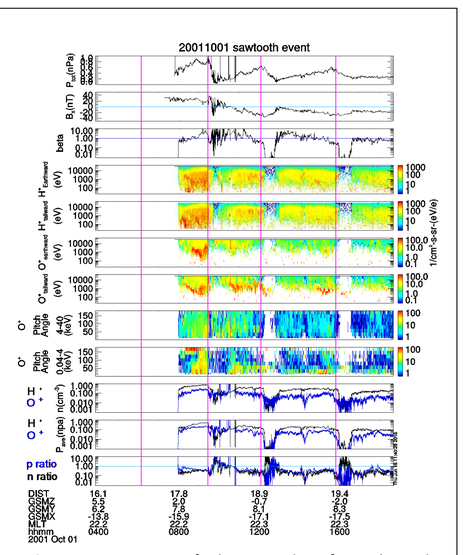

Figure 4. Overview of Cluster 1 data from the tail during the event. Injection time marked with magenta lines. The total pressure(top panel) shows the loading prior to, and unloading after the injection time, which is a typical for a substorm event, and also observed in sawtooth events.

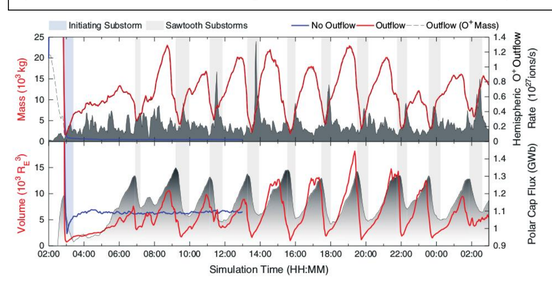

Figure 1. vertical shaded bars show expansion phase of substorm. They drive the O + outflow(dark shadow) in top panel, simulated by [Ouellette et al. 2013]

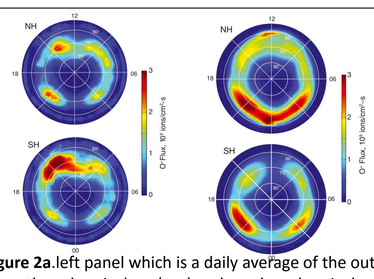

Figure 2a.left panel which is a daily average of the outflow flux in northern hemisphere(top) and southern hemisphere(bottom) for an SIR event in the simulation of [Brambles et al. 2013] and **Figure 2b.** right panel is the same for an CME event.

- Figure 3. shows the overall conditions for the storm on Oct 1, 2001 from two days before to two days after the event day. The Storm had a min-SymH of -150 nT. As it is a CME storm it was driven by a strong southward change on Interplanetary Magnetic Field.
- Figure 4. shows Four LANL spacecraft in the geosynchronous orbit to identify the sawtooth evets. A sawtooth event is a sequence of particle injection with fast increase and slow decrease. Injection time is when the rapid proton flux increased are observed by LANL satellites.
- Figure 5. gives the overview plot of Cluster 1 in the tail during the event time period. The total pressure(top panel) shows the loading prior to, and unloading after the injection time which is a signature of a sawtooth event.

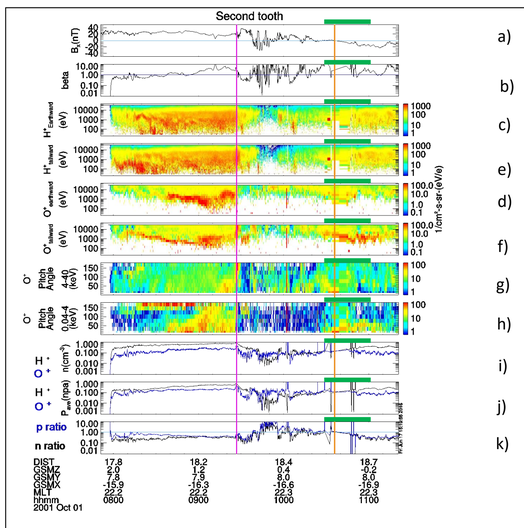

Figure 6. CLUSTER 1 data from 07: 51 to 11:30 UT on October 1, 2001. (a) Bx, (b) plasma beta, (c) Earthward H $^+$ energy spectrum, (d) tailward H $^+$ energy spectrum, (e) Earthward O $^+$ energy spectrum, (f) tailward O $^+$ energy spectrum, (g) pitch angle spectra for energy range of 4-40 keV, (h) pitch angle spectra for energy range of 0.04-4 keV, (i) H $^+$ (black) and O^+ (blue) density, (j)) H $^+$ (black) and O^+ (blue) pressure, (k) O^+ to H $^+$ density ratio (black) and O^+ to H $^+$ pressure ratio(blue)

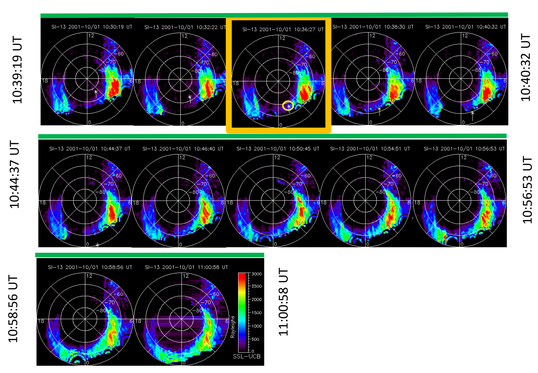

Figure 7. Selected IMAGE WIC from 10:30 UT on 1 October 2001 to 11:00 UT on 1 October 2001.Horizontal green lines above the images marked the period of time in correspond to the same time period in Cluster plot.

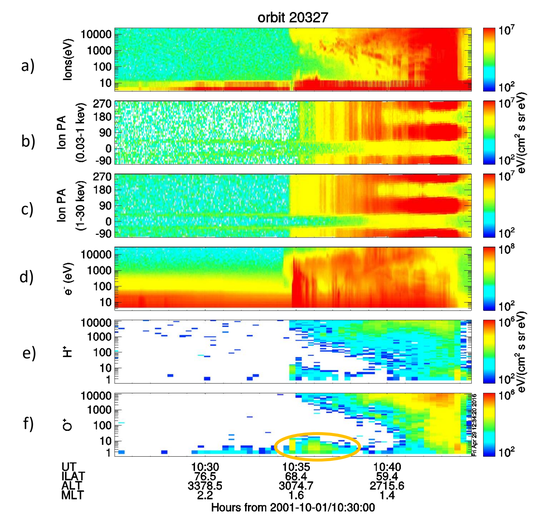

Figure 8. FAST observation from 10:20 UT on 1 October 2001 to 10: 45 UT on 1 October 2001 of closest pass after the injection time from the nightside aurora. (a) energy spectrogram of ions (H^+, O^+) from TEAMS, (b) pitch angle spectra of ion for the energy range of 0.03-1 keV, (c) pitch angle spectra of ion for the energy range of 1-30 keV, (d) e^- energy spectrogram from IESA, (e) H^+ energy spectrogram from TEAMS, (f) O^+ energy spectrogram from TEAMS. The magenta oval marked the O^+ outflow.

This second tooth is during the peak of the main phase of the storm. We find the following:

1) The Cluster data shows an intense flow of tailward energy-dispersed O^+ (panel f). The energy dispersion is a time of flight effect, with the more energetic O^+ reaching the spacecraft before the lower energy O^+. This is a clear signature of a a nightside auroral source, as shown in [Sauvaud et al. 2004]. The tailward signature is followed by an earthward energy dispersed feature (panel d), which is likely from the same source, bouncing back from the opposite hemisphere, a feature also observed in [Sauvaud et al. 2004]. Thus this tooth does show a strong auroral source filling the plasma sheet.

2) The Cluster data (panels i, j, and k) show that there is an increase in the H^+ and O^+ density and pressure during the growth phase, but the O^+ does not increase more than the H^+, with the ratio almost flat. Thus it is not enhanced O^+ that drives the onset.

3) There is only IMAGE data during the recovery phase of the event. The FAST satellite observes the outflow (time period shown with yellow box). The outflow is weak, and at low energy (<10 eV).

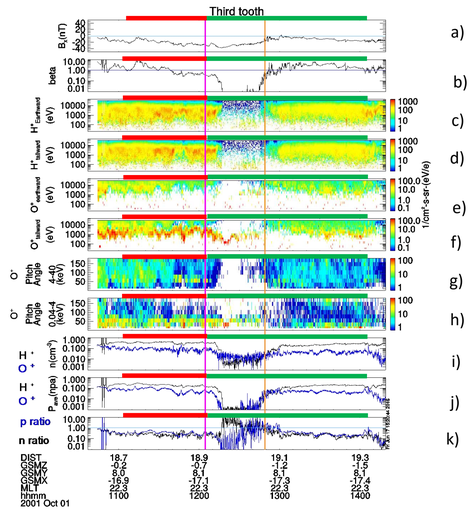

Figure 9. Same as Figure 5 for the time period of 10:15 UT, 1 October 2001 to 14:14 UT, 1 October 2001. Horizontal red lines define the time period of growth phase which IMAGE data is available.

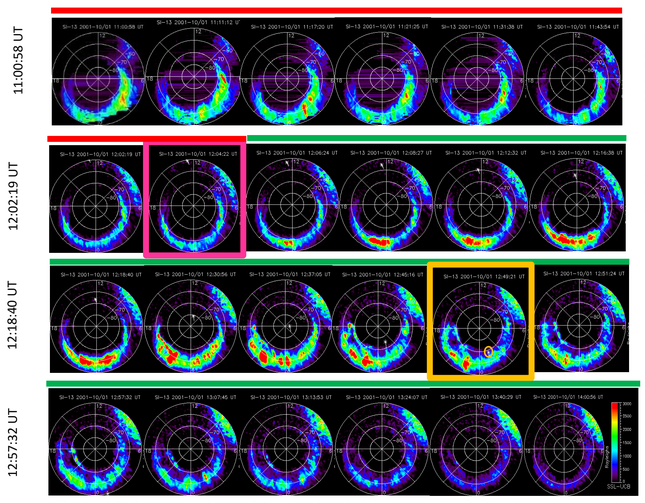

Figure 10. Same as Figure 6 the horizontal red bars above the images show the growth phase of tooth from 11:00 UT to 12:04 UT on 1 October 2001 and the horizontal green line shows the expansion phase of tooth from 12:06 UT to 14:00 UT on 1 October 2001. Magenta box marked the closest image to the injection time in the plasma sheet.

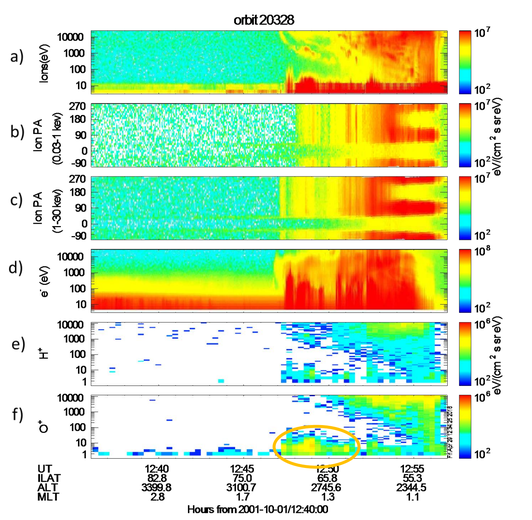

Figure 11. Same as Figure 7 closes pass after the injection time from the nightside aurora for the time period of 12:36 UT to 12:57 UT on 1 October 2001

This third tooth is during the recovery phase of the storm. We find the following:

1) The Cluster data shows tailward field aligned flows (panel f and pitch angles in panel h) that are observed continuing into the lobe. This is the signature of cusp outflow, which comes over the polar cap into the lobe, and then enters the plasma sheet, as shown in [Kistler et al. 2010]. The clear energy dispersed signatures of the nightside auroral source are not observed.

2) As in the first tooth, the O^+ pressure and density is not enhanced more than H^+. The ratio actually decreases during the growth phase. Again, it does not seem to be enhanced O^+ that drives the onset.

3) This event has good IMAGE data through the growth and expansion phase, and a FAST pass through the auroral zone (yellow box) just at the end of the expansion phase. While FAST doesn't pass through the peak of the aurora, it does pass through an active region. The outflow observed is relatively weak and low energy.

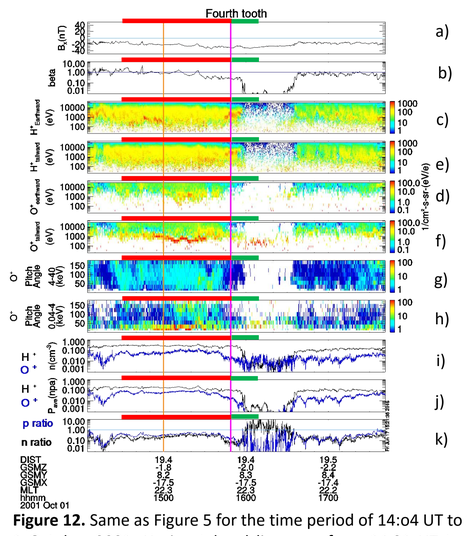

Figure 12. Same as Figure 5 for the time period of 14:o4 UT to 17:41 UT on 1 October 2001. Horizontal red lines are from 14:31 UT to 15:49 UT, 1 October 2001 and horizontal redline is from 15:49 UT to 16:09 UT, 1 October 2001.

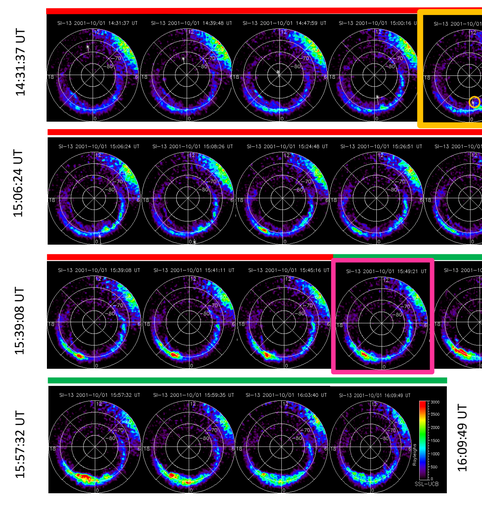

Figure 13. Figure 9. Same as Figure 6 the horizontal red bars above the images show the growth phase of tooth from 14:31 UT to 15:49 UT on 1 October 2001 and the horizontal green line shows the expansion phase of tooth from 15:49 UT to 16:09 UT on 1 October 2001. Magenta box marked the closest image to the injection time in the plasma sheet.

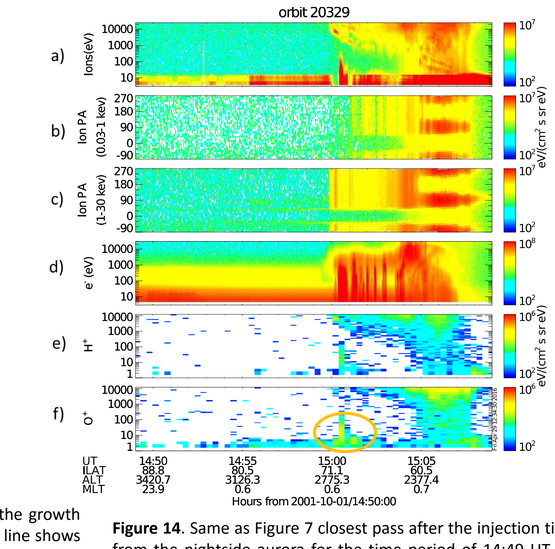

Figure 14. Same as Figure 7 closest pass after the injection time from the nightside aurora for the time period of 14:49 UT to 15:09 UT on 1 October 2001

The fourth tooth is also during the recovery phase of the storm. We find the following:

1) The Cluster data again shows tailward field aligned flows (panel f and pitch angles in panel h) that continue into the lobe, although the source is weaker now. This is most likely cusp outflow, as shown in [Kistler et al. 2010].

2) The O^+/H^+ ratio increases during the growth phase, but then decreases prior to onset. Again, it does not seem to be enhanced O^+ that drives the onset.

3) This event has good IMAGE data through the growth and expansion phase, and a FAST pass through the auroral zone (yellow box) during the growth phase. The auroral emissions and the outflow are both weak at this time.

Conclusions:

1) Do the O^+ in the magnetotail during each sawtooth have signatures of nightside outflow or does it come from the cusp?
The second tooth shows strong auroral outflow into the plasma sheet, consistent with the [Brambles et al. 2013] .
The 3rd and 4th teeth show the signatures of cusp outflow as the source of O^+ at the Cluster location (~19Re). Thus there is no evidence for continued feedback.

2)Is there evidence of increased O^+ pressure during the growth phase of each tooth?
The ratio of O^+ to H^+ does not increase significantly during the growth phase. This is inconsistent with an increase in O^+ driving the onset, as suggested by [Brambles et al. 2011].

3) Is there evidence for strong outflow after each expansion phase and during the growth phase?
This is difficult to measure because the FAST observations only give a local measurement and are usually not over the aurora right at onset. However, the nightside O^+ outflow observed by FAST during this event is relatively weak and low energy, even during the expansion phase observation in the 3rd tooth.

Overall, the sawtooth events observed during this CME event do not seem to be driven by a large flux of O^+that fills the plasma sheet.

References
Brambles et al. (2011), Science 332, 1183, doi:10.1126/science. 1202869
Brambles et al. (2013), JGR 114, A06201, doi:10.1002/jgra.50522
Kistler et al. (2010), JGR 115, A03209, doi:10.1029/2009JA014838
Ouellette et al. (2013), JGR 118, 3223–3232, doi:10.1002/jgra.50309
Sauvaud et al. (2004), JGR 109, A01212, doi:10.1029/2003JA009996