Activity Dependent $O^+$ Transport Paths From the Ionosphere to the Ring Current

W.K. Peterson$^1$, L. Andersson$^1$, B. Callahan$^1$, S.R. Elkington$^1$, R.W. Winglee$^2$, J.D. Scudder$^3$, and H.L. Collin$^4$

and thanks to Erika Harnett$^2$

$^1$University of Colorado, $^2$University of Washington
$^3$University of Iowa, $^4$Lockheed Martin

Paper SM 13E-05Fall 2007 Meeting, American Geophysical Union
Outline

- What do we know about O\(^+\) in the ring current?
- What do we know about O\(^+\) transport and energization during quiet and active times?
  - New information about the O\(^+\) source in boundary related coordinates at quiet times.
- O\(^+\) plasma sheet observations at quiet and active times
- Plasma sheet O\(^+\) from multi-fluid model runs at quiet and active times

**Conclusion:** There are two distinct pathways for the energization and transport of O\(^+\) from the dayside ionosphere to the plasma sheet and from there into the ring current.
What do we know about O\textsuperscript{+} in the ring current?

- Energetic O\textsuperscript{+} in the ring current dynamically alters the pressure balance during geomagnetic storms.
- Changing pressure in the ring current modifies its evolution.
- Almost all of our knowledge about pressure variations in the ring current and their effects comes from directly from models or inversions of ENA or magnetometer data.

Peterson et al. Fall 2007, AGU
Large scale models are required to tease out $O^+$ transport paths, energization mechanisms, and ring current pressure distributions from sparse data.

- Available *in-situ* observations are too sparse to tease out the pressure variations over a storm cycle.
- Inversion of ENA images and magnetometer data is heavily model dependent—especially on assumed initial conditions.

*Here we take a critical look at energization and transport of $O^+$ in dynamic coordinates at active and quiet times from the ionosphere to the ring current.*

Peterson et al. Fall 2007, AGU
What do we know about $O^+$ transport and energization during quiet and active times?

- **Ionospheric source**
  - Intensity increases with Dst --- Yau et al. 1988, Cully et al. 2003, and others
  - $O^+$ energy and flux at quiet times in boundary coordinates reviewed in this report

- **Plasma Sheet**
  - ISEE $-1 < R_E < 22$ reviewed in this report
  - Image ENA reviewed in this report
  - Multi-fluid code runs reviewed in this report
  - Cluster GSM$_Z$ cuts at 19 $R_E$

- **Ring Current**
  - Sparse *in situ* observations -- inadequate temporal resolution.
  - ENA and magnetometer inversions

- The data and model outputs presented here suggest that the $O^+$ transport path from the ionosphere through the plasma sheet to the ring current is activity dependent.

Peterson et al. Fall 2007, AGU
Boundary Related Coordinates.

- Casting O\(^+\) outflow in boundary related coordinates removes some of the “smearing” of average outflow data...allowing better mapping between the ionosphere and plasma sheet.

- How do we get boundary coordinates?
  - Polar boundary of the auroral oval identified in the energy and angular distribution of 100 eV electrons from Polar/Hydra.
  - Equatorward boundary of the auroral oval identified from loss cones in the ion distributions from Polar/Hydra.
  - Map observed O\(^+\) outflow from Polar/TIMAS into auroral zone and polar cap pseudo latitudes based on the times of auroral boundary crossings and the time the satellite reached its maximum latitude.
Net $O^+$ Outflowing Flux above 15 eV

Geomagnetically Quiet (Dst > -50)
0.015 < $E/q$ < 33 keV
acquired at ~ $2R_E$ during
solar minimum

MLT vs. INVL
$54^\circ < \text{INVL} < 90^\circ$

MLT Vs Pseudo Latitude:
10 Auroral Zone Bins
10 Polar Cap Bins

Fraction of outflow by
auroral zone MLT quadrant

- 40%
- 11% $O^+$
- 22%
- 27%

12 MLT 06
18 24

Most of the $O^+$ is on field lines connected to the flanks of the plasma sheet.

~3% of the observed $O^+$ energetic flux comes up in the polar cap.

Peterson et al. Fall 2007, AGU
Estimating Characteristic Energy

Pixel by pixel ratio

Characteristic Energy

ONLY Energies more than 2\(\sigma\) above zero are displayed

Missing \(O^+\) fluxes below the TIMAS cut-off energy (15 eV) bias the energy upward.....but NOT THAT MUCH!!!

Quadrant average \(O^+\) energies in keV

0.12
0.33\(\text{Energy}\) 0.17
0.59

Peterson et al. Fall 2007, AGU
Fluxes below the TIMAS cut-off energy (15 eV) bias the energy upward …..but NOT THAT MUCH!!!

- Upflowing thermal O+ flux at 50,000 km reported by Su et., al. (1998) is 8.3 x 10^4 ions/cm^2-s
- Assuming this flux is constant and has a characteristic energy of 1eV over the full auroral oval gives:

Quadrant average 
O+ energies in keV
at 6,000 km

<table>
<thead>
<tr>
<th>MLT</th>
<th>06</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>18</td>
<td>Energy 0.06</td>
<td>Energy 0.15</td>
</tr>
</tbody>
</table>

Are comparable with the energy derived from Fluxes > 15 eV

<table>
<thead>
<tr>
<th>Energy</th>
<th>0.33</th>
<th>0.59</th>
</tr>
</thead>
</table>
**O⁺ Outflow Observations During Storm Times (Dst < -50)**

- During storms both the noon and midnight sectors have significantly more outflow but their ratio is not known.

- The cartoon shows that O⁺ is expected to populate the plasma sheet near local midnight.

- The quiet storm time O⁺ source population is not consistent with the cartoon.

*Peterson et al. Fall 2007, AGU*
Summary of $O^+$ Source Characteristics

✧ Quiet times ($D_{ST} > -50$)
  ✧ Mostly from the dayside
  ✧ On field lines connecting primarily to the plasma sheet flanks
  ✧ Characteristic energy at 6,000 km: 100 - 200 eV

✧ Active times
  ✧ The source can be ten times more intense
  ✧ All MLT sectors have increased outflow but their relative increases are not known.

Peterson et al. Fall 2007, AGU
These data show that at quiet times the GSMy distribution of O\(^+\) is low and uniform and at active times the distribution is high and peaked near GSMy = 0.
Multi-Fluid Model Runs

March 18, 1997 Dst > -25 all day (1300 UT left 1500 UT right)

QUIET

Total density

Relative ionospheric H+ density

Relative O+ density

X  17  0  -35

Note O+ has a broad extent in the Y (dawn/dusk) direction

Peterson et al. Fall 2007, AGU
Multi-Fluid Model Runs

Oct. 29, 2003 Dst < -100 at 07:30 shown, larger later in the day

ACTIVE

View from IMAGE is not ideal

HENA image of 52-100 keV O⁺

Surfaces are at a total O⁺ density of 1.3 cm⁻³

Color indicates temperature

Note the narrow O⁺ extent in the Y direction

Peterson et al. Fall 2007, AGU
Summary of $O^+$ Plasma Sheet Characteristics

- Plasma Sheet Observations suggest
  - During geomagnetically quiet times ionospheric $O^+$ plasma convects primarily around the dawn and dusk sides of the magnetosphere.
  - During active times $O^+$ density and energy increase across plasma sheet but increase significantly more near the mid plane - $GSM_Y=0$.

- Multi-Fluid code results are consistent with the ISEE -1 observations
Summary of $O^+$ Source and Plasma Sheet Characteristics

- Observations and multi-fluid simulations show that there are two distinct pathways for the energization and transport of $O^+$ from the dayside ionosphere to the plasma sheet.

- **$O^+$ in the the plasma sheet is**
  - Less dense, less energetic, and approximately uniformly distributed in GSM$_Y$ during quiet times.
  - More dense, more energetic, and occurring primarily near the GSM$_Y = 0$ meridian at active times.

Peterson et al. Fall 2007, AGU
Conclusion/Discussion:

- The source of O\(^+\) in the ring current is the plasma sheet.
- Models used to explore ring current dynamics:
  - have not yet explicitly included the complete O\(^+\) activity dependent transport paths from the ionosphere to the ring current.
  - *have not directly addressed the effects of the O\(^+\) plasma in the pipeline between the ionosphere and ring current during transitions from quiet to active times.*
- New multi-fluid codes are coming on line and will be useful in addressing the unexpected complication of activity dependent O\(^+\) transport paths discussed here.
Extra Slides
It was not possible to identify both poleward and equatorward boundaries on every auroral zone crossing.

A file listing the auroral zone crossing times as well as the times that the Polar satellite reached its maximum southern latitude is available at

http://lasp.colorado.edu/timas/papers/Peterson/Polar_AZ_crossing_times.txt
Sampling

MLT vs. INVL
$54^\circ < \text{INVL} < 90^\circ$

MLT Vs Pseudo Latitude:
10 Auroral Zone Bins
10 Polar Cap Bins

There are big differences between the Pseudo and real ovals

9% of the auroral oval area is in the noon sector, 47% in the midnight sector.

Peterson et al. Fall 2007, AGU
Plasma Sheet H$^+$ Observations
McComas et al. (2002)

Two $D_{ST}$ Maxima
07:00/-175  13:00/-182

13:00 UT

Angular width of the plasma sheet at $X - 10 R_E$ for various energies

40keV

20keV

Peterson et al. Fall 2007, AGU