Ion Outflow at Mars Using MEX Ion And Electron Data

P21A-1702

C. M. Fowler[1], L. Andersson[1]

[1] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA

Conclusions:

- As Mars rotates the magnetic field loops associated with the crustal fields will compress on the dawn side and relax on the dusk side. For O^+ ions, on such flux loops, escape to space is easiest as a result of compression when compared to the expanding or static cases.
- Evolution of three magnetic cases considered in this study result in a cooling of the plasma since more energetic ions can more easily escape. The static case produced the most cooling.
- Compression and expansion of the magnetic fields result in changes in the pitch angle distribution of the O^+. The most notable pitch angle changes were associated with changes in the mirror point location.

1 Introduction, Previous Work

- Understanding the climate evolution of Mars is an important part of understanding the evolution of the planet itself.
- The two hemispheres of Mars are very different: north has a younger surface with few magnetic crustal fields; south has an old cratered surface with many magnetic crustal fields [Connerney *et al*., 2001].
- Previous study of Mars Express (MEX) data has shown large O^+ fluxes moving tailward in the northern hemisphere, and under certain conditions in the southern hemisphere (Fowler et al, Manuscript in preparation, 2013).
- In the Northern hemisphere the loss of O^+ was observed following the surface and then resulting in tail ward flow inside the Photoelectron region past 18 MLT.
- In the Southern hemisphere, significant O^+ fluxes were seen on the dayside but this did not result in a similar tail ward flow inside the Photoelectron region past 18 MLT.

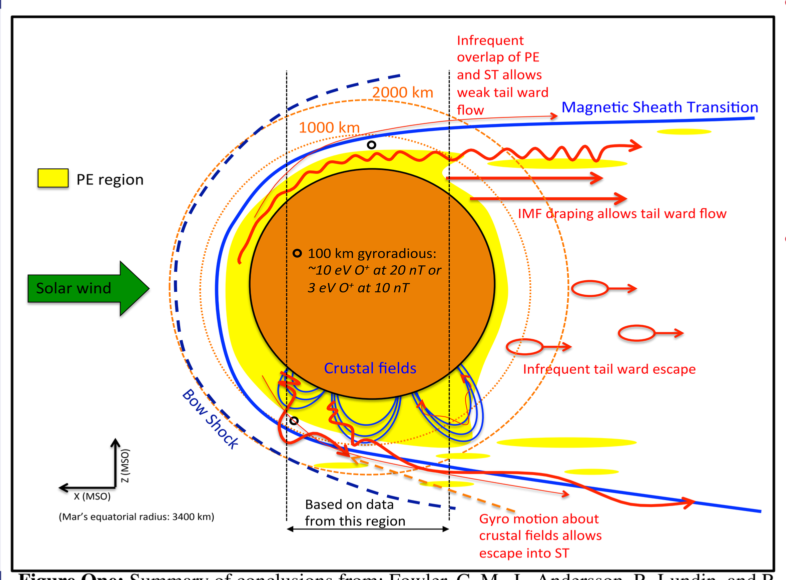

Figure One: Summary of conclusions from: Fowler, C. M., L. Andersson, R. Lundin, and R. A. Frahm, "Ion Outflow at Mars: A Possible Escape Channel in the Southern Hemisphere," J. Geophys. Res., Manuscript in preparation, 2013.

- Based on dusk observations, when the magnetic sheath boundary is compressed to low altitudes (< 500 km) O^+ fluxes increase by over an order of magnitude in the Southern hemisphere, becoming comparable to the Northern tail ward flows.
- Complex magnetic topology in south is thought to be the cause of this. Combination of solar wind IMF, magnetic crustal sources and rotation of planet results in a continuously changing magnetic topology. If $\tau_{AB} < \tau_{O+gyro}$ then the magnetic adiabatic invariant is broken and ions can heat and end up on a different flux tube. Hot O^+ can reach higher altitudes where gyro motion in combination with magnetic field gradients can result in O^+ moving from trapped flux tubes to escaping down the Magnetic Sheath boundary.

2 Aims Of Study

- Analysis of MEX data suggests that in regions of crustal fields heavy ions (O^+) can more easily reach higher altitudes and to the sheath boundary.
- Determine the ability of O^+ trapped on crustal fields to escape to higher altitudes as Mars rotates via particle tracing.
- Can the compression and/or relaxation of a magnetic dipole allow a significant number of O^+ to escape into space?
- Based on dusk observations from the MEX mission the boundary region of the sheath is usually at 1000 – 1200 km but can vary between ~400 to ~1800 km.

3 Model

- Particles (here O^+) are initiated in a crustal magnetic field and followed to see if they can escape the closed field into the sheath.
- The model magnetic field consists of three magnetic field sources: **magnetic dipole** representing the Martian crustal field (constant), the **solar wind IMF** (constant) and **current sheet magnetic field** (variable in time, allowing the sheath boundary change altitude). See Figure 2.
- Model solves the Lorentz force with gravity using Leap Frog algorithm. Model doesn't include: solar wind dynamic pressure, particle pressure, magnetic pressure, chemistry, electric field, collisions.
- The simulation is seeded with 6000 O^+ in a 3D box following a Maxwellian energy distribution. Population is isotropic in X and Y and follows an altitude profile in Z from (Nier & McElroy, 1977). Only below the current sheet altitudes (which can vary through the simulation) are O^+ produced through out the simulation.

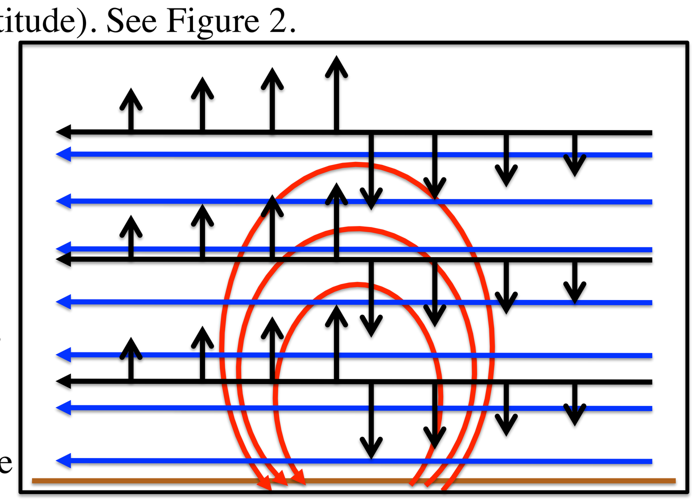

Figure Two: The three magnetic fields which are linearly summed in the model.

- To represent photochemical production a smaller number (250) of O^+ is seeded every 100s within the box. The new O^+ follows the same altitude profile and temperature and is only initiated below the current sheet as the initial population was.
- For all simulation cases the current sheet altitude was set at 1000 km and the simulation run for one hour to "warm up" so that the O^+ population reaches some kind of equilibrium.
- This study then evaluates three different scenarios:
  (1) Static: current sheet stays at 1000 km for a six hour period.
  (2) Relaxation – represents dusk case: current sheet moves linearly from 1000 to 1600 km at a steady rate over a six hour period.
  (3) Compression – represents dawn case: current sheet moves linearly from 1000 to 400 km at a steady rate over a six hour period.
- When O^+ leaves any of the six sides it is assumed lost and removed from the simulation. The two major loss regions evaluated in this study are:
  1. O^+ above the current sheet is assumed to be lost to space.
  2. O^+ below 150 km altitude is assumed to be lost to the atmosphere from recombination.
- When O^+ is lost it's location, velocity, and lifetime within the simulation is recorded.

4 Starting Magnetic Topology and Case 1: Static

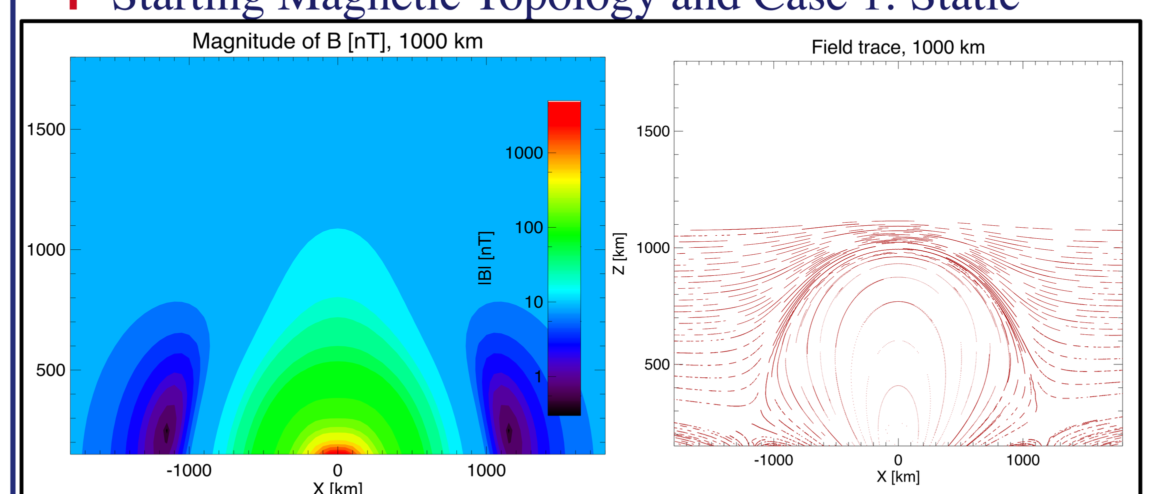

Figure Three: The starting magnetic field topology for the three cases. Left: Contour plot of magnetic field strength in nT. Right: Magnetic field direction presented as a particle trace of field aligned particles.

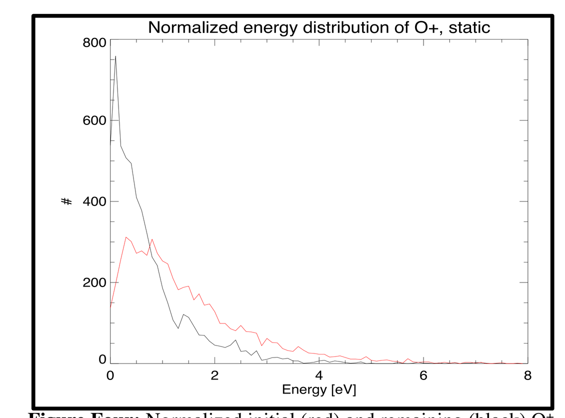

Figure Four: Normalized initial (red) and remaining (black) O^+ energy distributions for case 1.

- Plasma cooled. See Figure 4.
- Pitch angle distribution changes slightly: field aligned particles lost to atmosphere. See Figure 5.
- The more field aligned the seeded particles are the more likely they will be lost into the atmosphere resulting, in a less isotropic population.
- The more energy the ions have, the more likely they will experience the changing magnetic fields at the outer edge of the crustal field, resulting in possible escape.

	Case 1 (Static)	Case 2 (up)	Case 3 (Down)
Start #	5671	5544	5923
End #	7421	8010	3802
Seed Energy (eV)	1.0	1.0	1.0
Seed Step (s)	100	100	100
Seed #	250	250	250
Total # seeded	54000	54000	54000
Warm up (hrs)	1	1	1
Sim time (hrs)	6	6	6
Loss to space (#)	6255	3879	12566
Lost to atm (#)	19418	18822	19992
Ratio (s/(s+atm))	0.24	0.17	0.39

Table One: Results from all three case runs.

- Low energy ions will not move much during the simulation, however, gravity will cause them to diffuse downward, and they are more likely to be lost into the atmosphere.

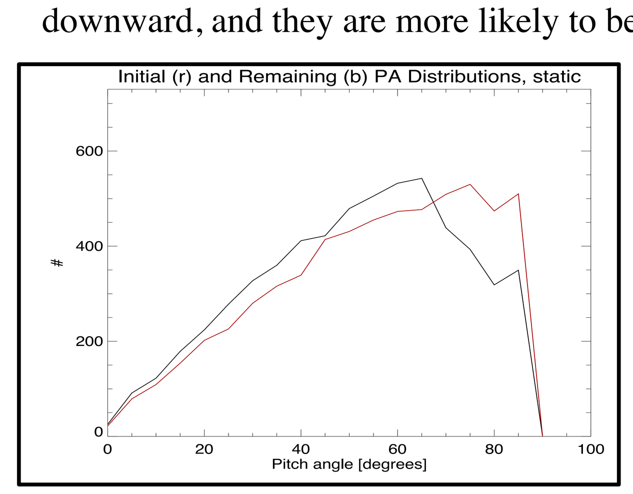

Figure Five: Normalized initial (red) and remaining (black) O^+ pitch angle distributions for case 1.

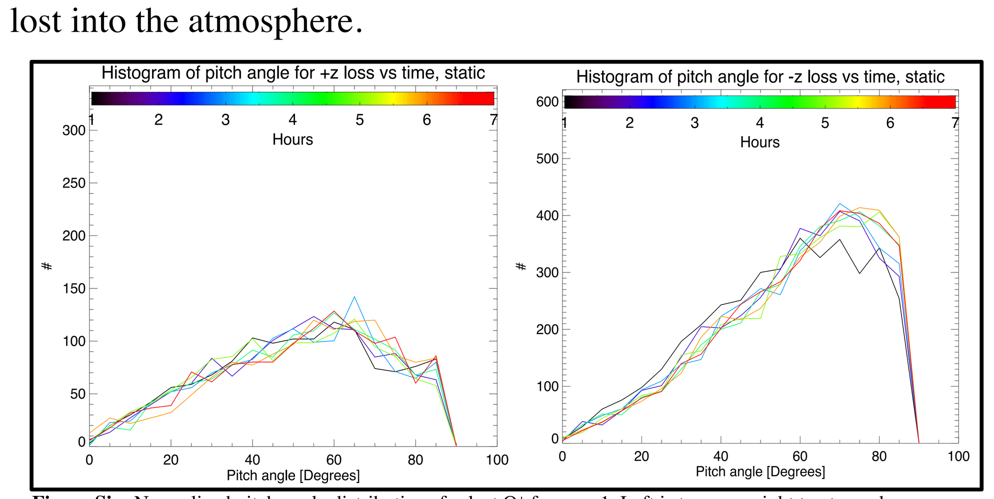

Figure Six: Normalized pitch angle distributions for lost O^+ for case 1. Left is to space, right to atmosphere. Color is time in one hour bins.

- Figure 6 shows the evolution of the pitch angle distribution of O^+ lost to space (left) and atmosphere (right). Each colored distribution represents the ions lost over that hour color coded according to the bar at the top of the figures. As can be seen, after the initial warm-up hour the distribution is constant as expected.

5 Case 2: Relaxation

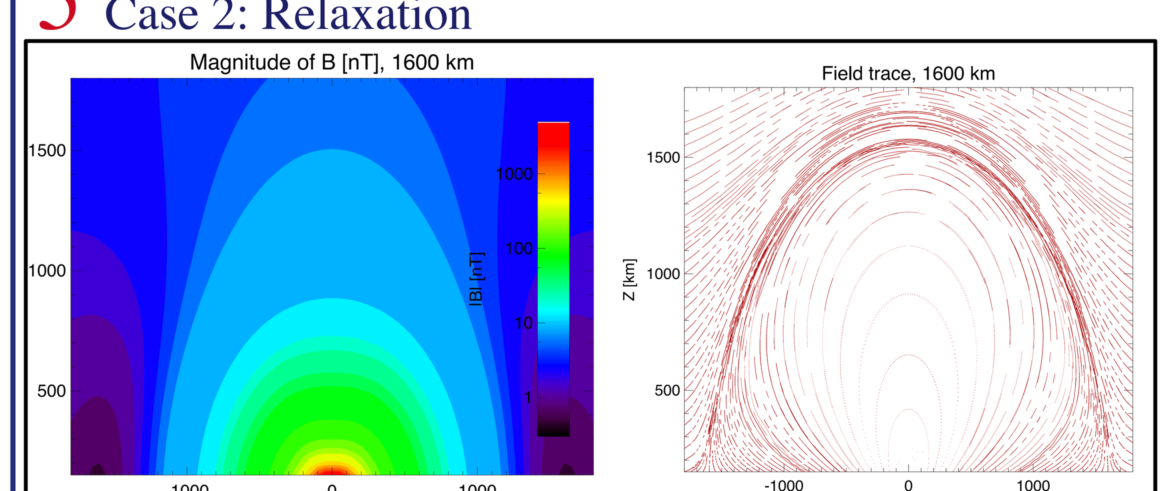

Figure Seven: Contour plot of magnetic field strength in nT (left), and a particle trace (right) of the final magnetic topology for case 2.

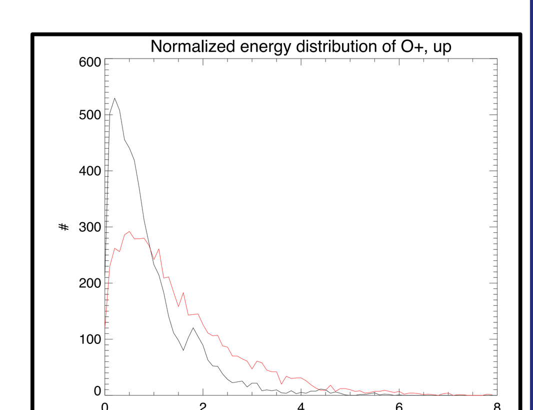

Figure Eight: Normalized initial (red) and remaining (black) O^+ energy distributions for case 2.

- Cooling effect similar to that of case 1 (Figure 8).
- Pitch angle distributions are constant compared to case 1 (Figure 9).
- Loss to space decreases as current sheet moves up. Age of lost particles decreases as current sheet moves up. Suggests that only newly seeded particles escape as current sheet moves up – those seeded near it.

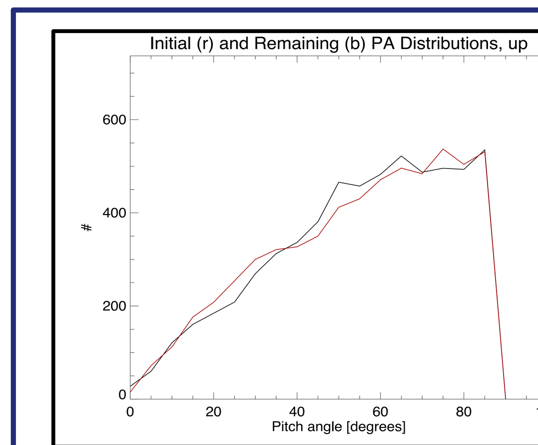

Figure Nine: Normalized initial (red) and remaining (black) O^+ pitch angle distributions for case 2.

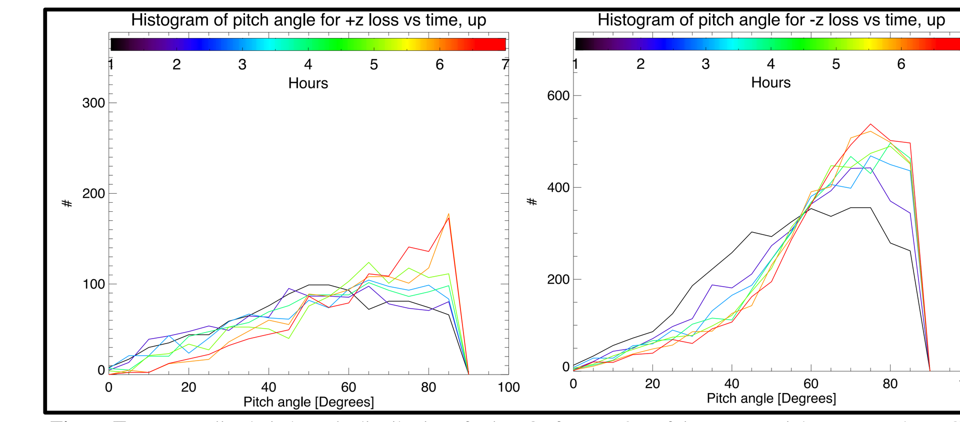

Figure Ten: Normalized pitch angle distributions for lost O^+ for case 2. Left is to space, right to atmosphere. Color is time in one hour bins.

- Loss to atmosphere is ~ constant, with a slight increase towards the end of the simulation.
- Age of lost particles plateaus, suggesting system is coming to equilibrium, similar to case 1.
- The pitch angle distribution of O^+ lost into the atmosphere changes with time (Figure 10). The increasing 90° angles suggest that the O^+ mirror points move to lower altitudes as the current sheet moves to higher altitudes. This would explain the slight increase in total number lost with time.
- In a study of a magnetic storm event at Earth when |B| increases (opposite to case 2) Tu & Li [2011] showed that the the mirror points rise during a magnetic storm at Earth, supporting an increase of loss to atmosphere as observed for case 2.
- For loss to space more 90° pitch angle O^+ escapes with time (Figure 10).

6 Case 3: Compression

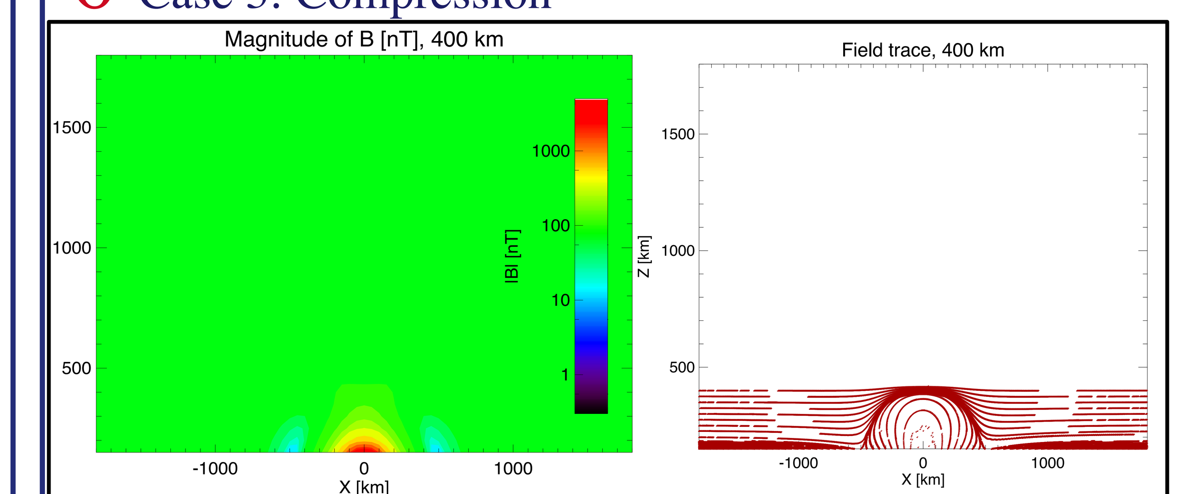

Figure Eleven: Contour plot of magnetic field strength in nT (left), and a particle trace (right) of the final magnetic topology for case 3.

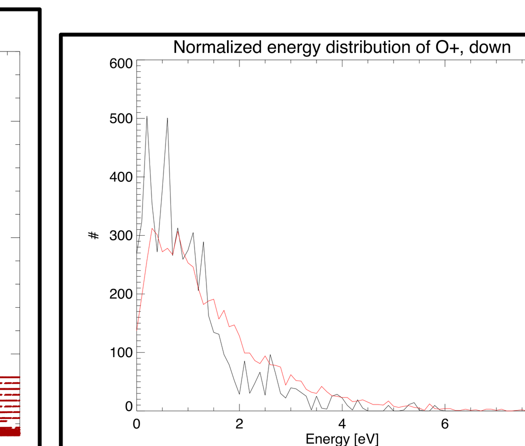

Figure Twelve: Normalized initial (red) and remaining (black) O^+ energy distributions for case 3.

- Case 3 has the largest loss both absolute and relative compared to cases 1 and 2 (Table 1).
- Plasma cools slightly from initial to end population (Figure 12). Pitch angle distribution changes (Figure 13). Since mirror points move outward (for increasing |B|) the number of 90° particles lost to the atmosphere decreases.
- Loss to space increases as the current sheet moves down in altitude. The age of these particles also increases, suggesting that particles that were trapped in the magnetic field at lower altitudes (bouncing between mirror points) are able to escape upward.
- Loss to atmosphere is ~constant over time, but there is a peak in age ~half way through the simulation. As the current sheet moves down, the volume in which particles can be seeded decreases, increasing the density of young, seeded particles.

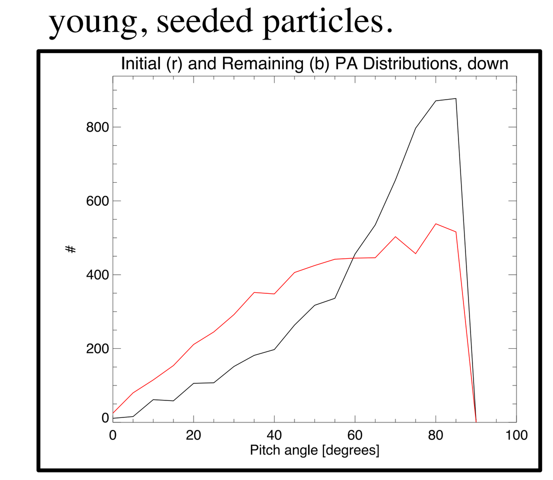

Figure Thirteen: Normalized initial (red) and remaining (black) O^+ pitch angle distributions for case 3.

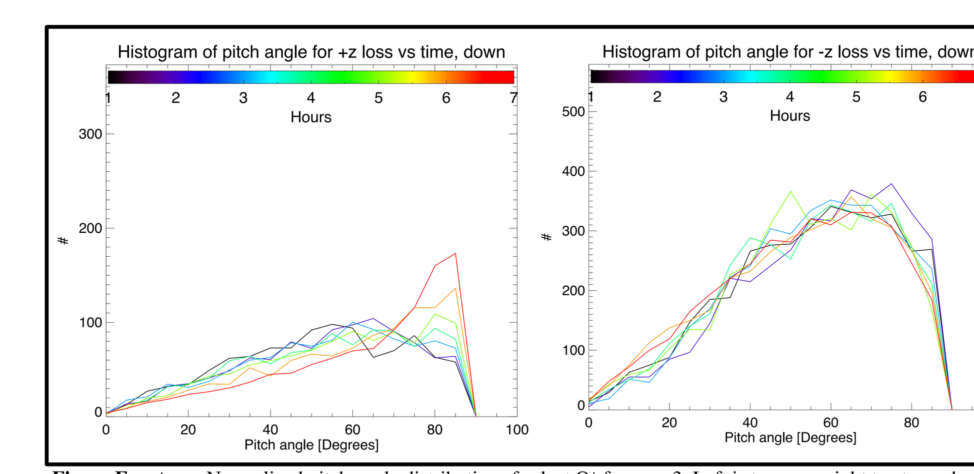

Figure Fourteen: Normalized pitch angle distributions for lost O^+ for case 3. Left is to space, right to atmosphere. Color is time in one hour bins.

- Pitch angle distributions of lost O^+ throughout time to space do not change much. As a result of the mirror points moving to higher altitudes, fewer 90° particles are lost into the atmosphere with time (Figure 14).

7 Summary and Discussion

- Significant O^+ escape into the sheath boundary region is possible under the compression of a dipole. The efficiency of this escape increases with increased compression.
- The level of boundary compression from the solar wind at the sub-solar boundary location will directly impact the possibility of flooding the boundary region on the dusk side with O^+.
- In the previous study of MEX O^+ dusk ions, O^+ fluxes in the boundary region were significant during cases of solar wind compression.
- The three simulation cases were chosen to start from the same initial condition. The dawn case (compression) therefore has the largest changes in B, due to the $1/r^3$ nature of a dipole. The dusk case (relaxation) escape rate was similar to the static case, hence the dawn compression is more important than the dusk relaxation.
- The static or the compressed case alter the pitch angle distribution. The relaxation case has little effect on pitch angle distribution.
- A non-static magnetic topology will significantly alter the pitch angle distributions of escaping O^+. The possibility of heating as a result of coupling to the solar wind natural fluctuations suggests that the magnetic field topology in the vicinity of the crustal fields will provide a means to move heavy ions out to the sheath boundary.

E-mail: christopher.fowler@lasp.colorado.edu