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Low energy (keV) O^+ ion outflow directly into the inner magnetosphere: Van Allen Probes observations

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Abstract

The heavy ion component of the low-energy (eV to hundreds of eV) ion population in the inner magnetosphere, also known as O^+ torus, is a crucial population for various aspects of magnetospheric dynamics, such as the solar wind - magnetosphere coupling, the source for the ring current O^+ population, and propagation of ULF waves. Although the effects of high latitude and cusp ionospheric O^+ outflow and its subsequent transport and acceleration within the magnetotail and plasma sheet have been extensively studied, the source of low-energy O^+ within the inner magnetosphere remains a compelling open question. The HOPE instrument [4] aboard each of the Van Allen Probes [8], moving in highly elliptical, equatorial orbits with apogee of 5.8 R_E, has repeatedly detected low-energy O^+ field-aligned enhancements. We present a comprehensive study of one such event, where low energy O^+ field-aligned intensity enhancements were observed, both in parallel and antiparallel to the magnetic field direction, during a geomagnetic storm. The energy spectrogram exhibited a dispersive signature and a banded structure, features that our simple particle tracing simulation demonstrated are due to O^+ ions outflowing from both hemispheres of the night-side ionosphere directly into the magnetosphere within L = 4, and subsequently bouncing from one hemisphere to the other. These outflows are associated with field-aligned Poynting flux enhancements and field-aligned electron beams, as observed at the Van Allen Probes location, revealing energy transport from the magnetosphere to ionosphere as well as simultaneous field-aligned electron heating. We also incorporate in our study ionospheric measurements, such as field-aligned currents, as those are inferred by AMPERE data. The combination of simultaneous magnetospheric and ionospheric observations allows us to investigate for the first time the processes that lead to an O^+ outflow event from the low-latitude, night-side ionosphere directly into the inner magnetosphere. The ubiquity of such events in the Van Allen Probes data during geomagnetically active times might reveal one of the sources for the O^+ torus.

1. Introduction

Heavy ion mass loading is crucial for plasmapause and plasmasphere density studies. Mass loaded densities (as opposed to H^+ density profile) are important for accurate location of the plasmapause, and definition of that location is, in turn, necessary for meaningful calculation of the field line resonance radial frequency profiles of Ultra Low Frequency (ULF) hydromagnetic waves in plasmasphere [3]. Yet the source of this low energy heavy ions so deep into the inner magnetosphere is still under debate.

Early studies, using data from the retarding ion mass spectrometer (RIMS) on Dynamics Explorer 1 (DE 1) with elliptical polar orbit (675 km altitude and apogee of 24,875 km altitude), reported low-energy (<50 eV) O+ outflows with sources at the dayside cusp, auroral zone, and polar cap [5]. A statistical study of conic distributions (pitch angles 0^o – 90^o or 90^o – 180^o) of O+ ions < 100 eV was also conducted using data from the ISEE 1 spacecraft in highly elliptical orbit of 30^o inclination to the equator and 22.5 R_E apogee [6]. They separated the distributions in i) unidirectional, in which ions are emerging essentially from only one hemisphere, typically observed on higher L shells (that is, high geomagnetic latitudes or large geocentric distances or both), and ii) bi-directional distributions in which ions are seen coming from both hemispheres, typically observed on lower L shells. More recently, short bursts of low energy (<100 eV) field aligned ions were reported, using CIS/CODIF data on board Cluster spacecraft, which were interpreted as indication of low latitude outflow [12].

In the Van Allen Probes era, there have been a few studies reporting the occurrence of O+ conic distributions and attempting to explain the cause of such events. It has been shown that dispersive Alfvén waves observed in the inner magnetosphere during geomagnetic storms could extract O^+ ions from the topside ionosphere [1, 2]. A year-long statistical study of dipolarization events in the inner magnetosphere revealed that 80% out of 72 events were accompanied by field-aligned energy-dispersed O^+ ions that were extracted from the ionosphere nearly simultaneously to the onset of the dipolarization [9]. Yet these studies have mainly focused on outflows observed when the spacecraft are around their apogee (that is L ~ 6).

In this paper, we present a comprehensive study of a bi-directional outflow event, which occurred during the main phase of a storm, inside L ~ 4 and extending to L shells right outside the plasmapause. We combine in-situ particle and electromagnetic field data from the Van Allen Probe B in coordination with ionospheric measurements in order to address the possible mechanisms that lead to the outflow. Finally, we investigate the effect of this outflow on the density in the vicinity of the plasmapause.

2. Overview of the June 23 2015 O^+ outflow event

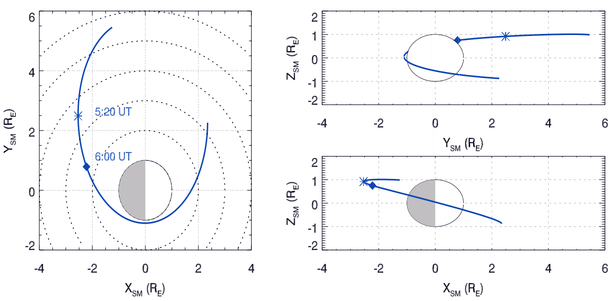

Figure 1. Van Allen Probe orbit in XY, YZ, and XZ planes in SM coordinates.

Figure 1 shows the orbit of the Van Allen Probe B in XY, YZ and XZ planes in SM coordinates from 3:00 UT until 7:00 UT on June 23 2015. During the time interval of interest (5:20 UT – 6:00 UT) the Van Allen Probe B, located in the pre-midnight sector, is approaching perigee.

In Figure 2 we show the main observations associated with the outflow event of interest. From top to bottom we plot: SymH (black) and AL (red) indices, 20-second averaged field-aligned poynting flux calculated using the perturbations of electric and magnetic field in magnetic field aligned (mfa) coordinates, pitch angle distributions for 47, 470 and 930 eV electrons, and O^+ fluxes for pitch angles 18°, 90° and 162°. The electric and magnetic field measurements were acquired from the EFW [11] and EMFISIS [7] experiments while the particle data were acquired from the HOPE experiment, all instruments aboard Van Allen Probe B. Throughout the interval 3:00 – 6:00 UT, a geomagnetic storm is in progress (Sym-H ~ -200 nT). After ~5:20 UT the AL decreases from ~ -200 nT to ~ -1000 nT indicating the expansion phase of a geomagnetic substorm. Starting at 5:20 UT and until 6:00 UT, we observe bi-directional field aligned O^+ flux enhancements (both at 18° and 162° pitch angles, with 162 pitch angle ions arriving first at the spacecraft), occurring near perigee, with very clear energy dispersion and multiple bands of these dispersive enhancements. Around the same time when these field aligned enhancements are first observed, there is also significant enhancement of the field-aligned poynting flux and bi-directional heating of ~ 47 eV electrons (enhancement of fluxes both at ~ 0° and ~ 180° pitch angles). Note that a different outflow event is observed at 162° only even earlier (~3:20 UT - ~5:10 UT), when the spacecraft was around its apogee, also associated with field-aligned poynting flux enhancements and bidirectional electron beams. However, that outflow event is not the focus of this study.

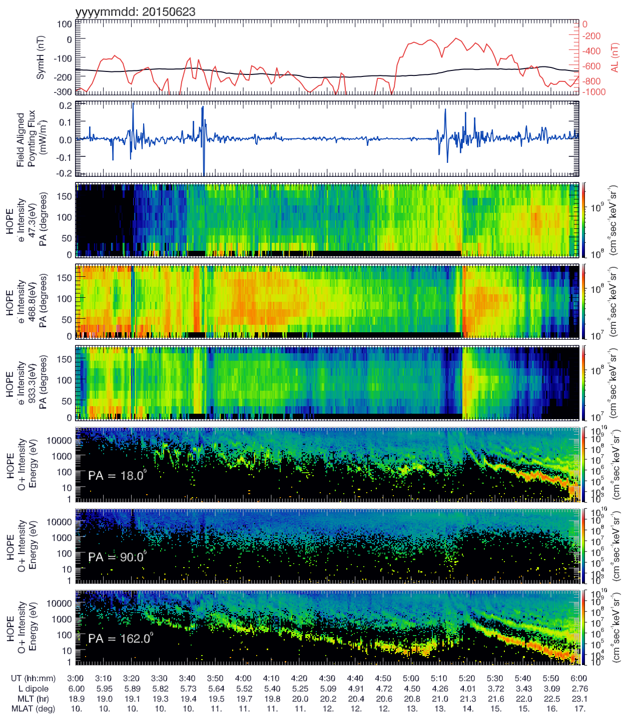

Figure 2. From top to bottom: SymH (black) and AL (red) indices, field-aligned poynting flux calculated by using the perturbations of electric and magnetic field in magnetic field aligned (mfa) coordinates, pitch angle (PA) distributions for 47, 470, and 930 eV electrons, and O+ fluxes for PA = 18°, 90°, and 162°.

Summarizing the event, during the main phase of the June 23 2015 storm we observe bi-directional O^+ outflow directly into the inner magnetosphere, inside L ~ 4. The outflow occurs during the expansion phase of a substorm, and coincides with field-aligned Poynting flux enhancements, indicating energy transfer from equatorial magnetosphere along the magnetic field lines and down to ionosphere, and field-aligned electron heating, which has been shown to stimulate ionospheric ion upflows [1, 2]. Investigation of the ionospheric field aligned current response from the AMPERE experiment (http://ampere.jhuapl.edu/) (not shown) reveals that the ionospheric footpoint of Van Allen Probe B at 5:20 UT was at the vicinity and slightly northward of a very intense upward field aligned current extending below 60^o in latitude, indicating electron precipitation, which has been associated with ionospheric outflow [10]. For the next 40 minutes the spacecraft's footpoint is moving equatorward into the region of the upward field aligned current.

3. Understanding the spatial-temporal evolution of the outflow event: particle tracing simulations under guiding center approximation.

Next, we incorporate in our study a modelling framework in order to understand the banded structure and the spatial-temporal evolution of the outflow event of interest. At 5:20 UT, we launch individual particles with energies 6, 10, 21, 46, 98, 211, 453, 716, 1132, and 2834 eV, at 1000 km, right outside the loss cone, from both the northern and southern hemisphere, and at an L shell range from L = 4 to L = 3, every 0.1 L (L = 4, 3.9, 3.8, etc.). For the next 40 minutes we trace the particles in a 2D meridional plane, using the guiding center approximation, under dipole magnetic field, and uniform electric field of 1mV/m perpendicular to the plane, so that we include the **E**x**B** drift of the particles towards the Earth as they bounce along the field lines.

Figure 3 demonstrates the comparison between our simulation and the observed O^+ fluxes. The black-white spectrogram shows the O^+ fluxes as observed by the HOPE instrument for pitch angles 18^o and 162^o (same as in Figure 2). On top of the spectrogram we mark with circles (triangles) the time stamps at which the particles of different energies, initially launched from the northern (southern) hemisphere, encounter the spacecraft along their bouncing motion and earthward drift, as the spacecraft is moving along its orbit from higher to lower L shells. The color of the symbols indicates the initial L shell at which the particles were launched at 1000 km.

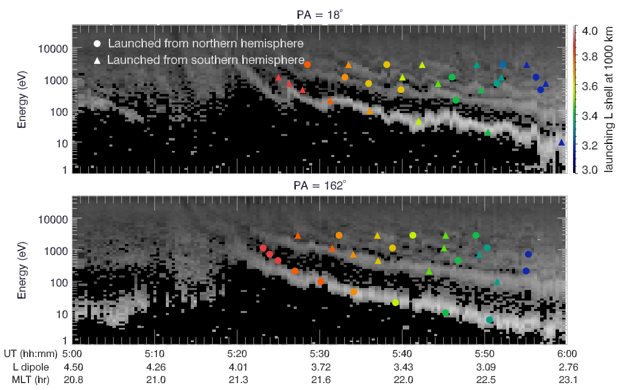

Figure 3. Black-white spectrograms: HOPE O^+ fluxes as observed for pitch angles 18^o (top panel) and 162^o (bottom panel). Symbols: simulated O^+ ions that encounter the spacecraft and were launched from the northern (circles) and the southern (triangles) hemisphere at 5:20 UT.

From Figure 3 it can be clearly seen that the multiple bands in the spectrogram are caused because O^+ ions of different energies that are launched from the ionosphere at different L shells, encounter the spacecraft at different times and L shells along the spacecraft's orbit. Another important aspect of the comparison between the data and our simple model is that in order to explain the field aligned O^+ flux enhancements at L shells as low as ~ 3 it is required that we launch O^+ ions from the ionosphere at these low L shells. Therefore, under an electric field of 1mV/m, which is a typical value for the inner magnetosphere, the **E**x**B** drift is not strong enough to push the particles at lower L shells as they bounce from one hemisphere to the other.

Our simple simulation demonstrated that the observed energy spectrogram is a result of a short time-scale ionospheric outflow (the outflow in our simulation was instantaneous) of O^+ ions with energies < keV, from both hemispheres, covering a latitudinal extent from L = 4 to L = 3. We have run simulations varying the time-scale and latitudinal extend of the O^+ ion outflow, as well as varying the electric field strength under which we trace the ions (results not shown), and we have found that the setup we present here fits the data best.

4. Effect of the O+ outflow on inner magnetosphere density

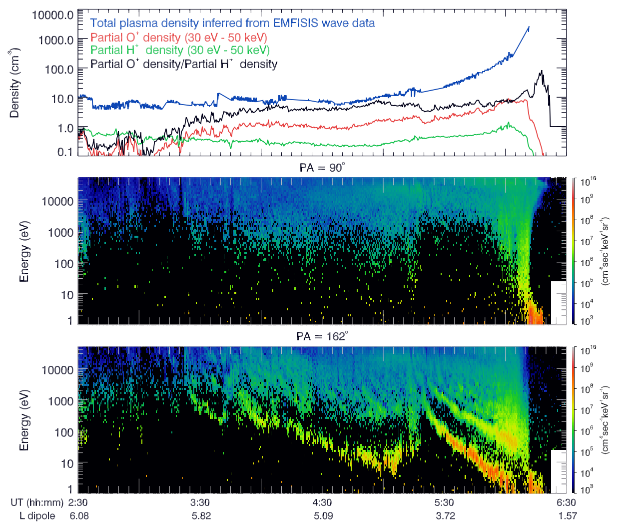

Figure 4. Top panel: Total plasma density as inferred from plasma wave data measured by the EMFISIS instrument (blue), partial density of 30 eV - 50 keV O^+ ions (red), partial density of 30 eV - 50 keV H^+ ions (green), ratio of O^+/H^+ densities (black). Middle panel: fluxes of 90^o pitch angle O^+ ions. Bottom panel: fluxes of 162^o pitch angle O^+ ions.

In the top panel of Figure 4 we show total plasma density as inferred from plasma wave data measured by the EMFISIS instrument (blue), and the partial density of 30 eV - 50 keV O^+ ions (red), partial density of 30 eV - 50 keV H^+ ions (green), the ratio of the last two (black) as acquired from the HOPE instrument. It is evident that whenever O^+ density dominates that of H^+, it is entirely due to ionospheric outflow, as it can be seen by the comparison between the 90° (middle panel) and 162° (bottom panel) pitch angle O+ fluxes. In particular the dominance of O^+ density closer to perigee and right around plasmapause, associated with the outflow event we have presented in this study, could indicate the formation of O^+ torus with all the implications we discussed in the introduction.

5. Acknowledgements

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6. References

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