Temporal evolution of H⁺ spectral structures during a geomagnetic storm: Observations and modeling

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1. Abstract

During the last decades several missions have recorded the presence of dynamic spectral features of energetic ions in the inner magnetosphere. We present a case study of the temporal evolution of H^+ spectral structures throughout the geomagnetic storm of 2 October 2013. We use data from the HOPE instrument onboard Van Allen Probe A to analyze the spectral structures in the energy range of 1-~50 keV. We find that the characteristics of the H^+ structures follow a cyclic pattern, the observed features changing dramatically as the storm starts and then returning to its initial pre-storm state. We use a model of ion drift to reproduce the spectral features. We further investigate the formation of multiple-nose structures by analyzing the drift trajectories with stationary and time-dependent model inputs. The results show that time-dependence is necessary to reproduce multiple noses and that these are the result of a time-of-flight effect of the drifting ions with different energies.

2. Introduction

- Over the last 40 years several magnetospheric missions have detected ion structures which in the energy-time spectrograms appear as narrow energy bands, or "nose-like" structures [*Smith and Hoffman*, 1974; *Vallat et al.*, 2007; *Dandouras et al.*, 2009].
- The formation of these structures is credited to the combined effects that the electric and magnetic fields, ion losses, and changes in the plasma sources and field configuration have on the particles being injected into the inner magnetosphere.
- Several studies of nose structures have found a dependence on geomagnetic activity, with multiple noses been observed more often during quiet times [*Fennel et al.*, 1998; *Li et al.*, 2000; *Ferradas et al.*, 2016]. This dependence has also been found in modeling results [*Buzulukova and Vovchenko*, 2008].

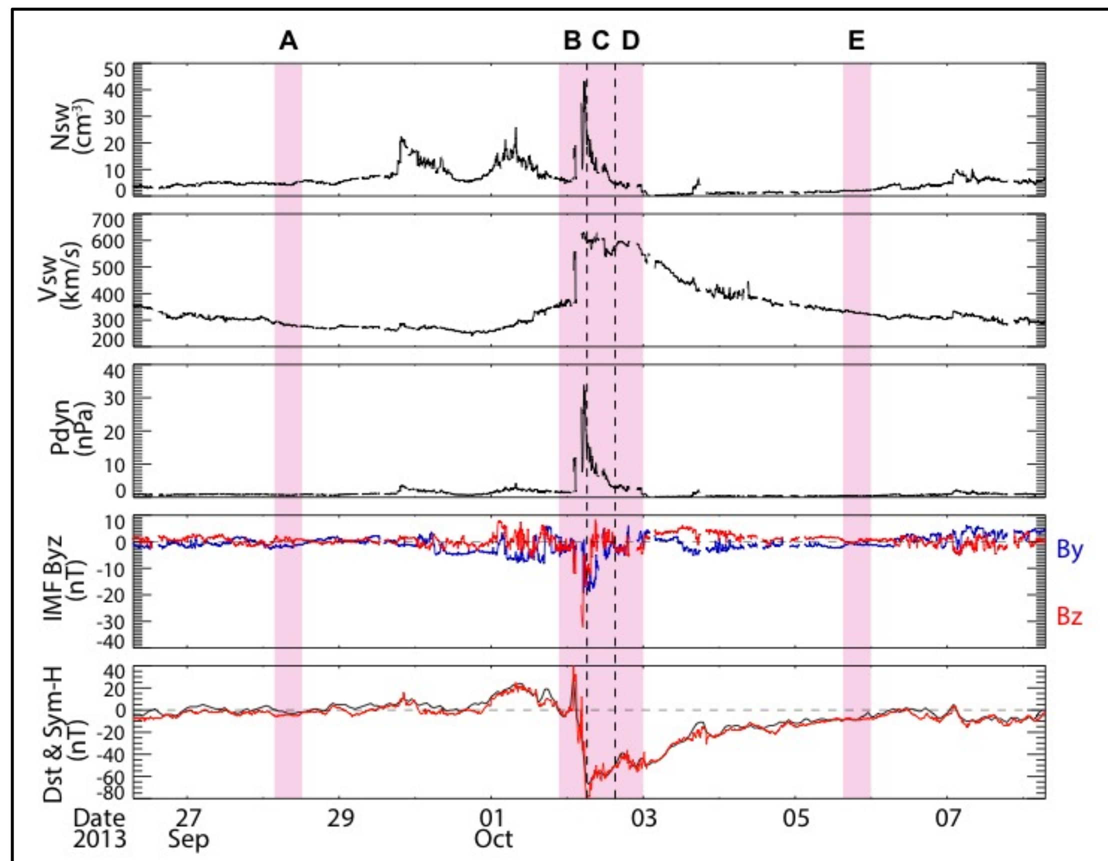
3. Motivation

- Report a case study of the temporal evolution of H^+ spectral structures during a geomagnetic storm.
- Validate the effectiveness of a model of ion drift and loss in the inner magnetosphere, using a dipole magnetic field and an empirical electric field model, to reproduce the H^+ structures.
- Investigate the formation mechanisms of single- and multiple-nose structures.

4. Instrumentation

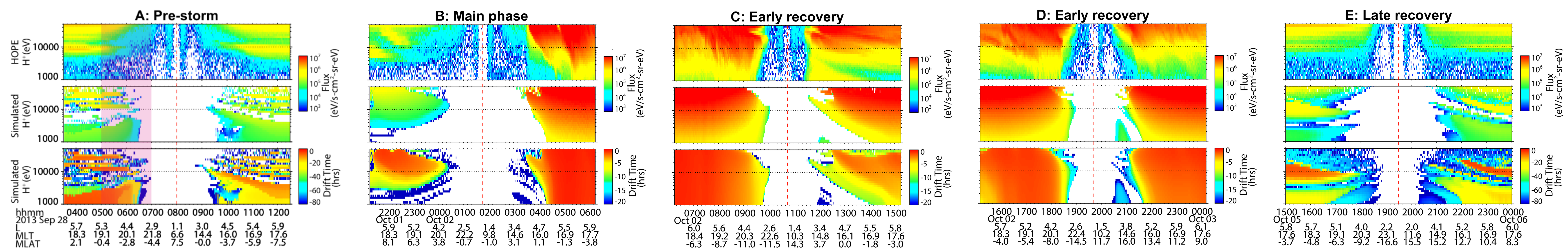
- The Van Allen Probes mission (2012-present) consists of two spacecraft (Probes A and B) in almost the same highly elliptical, low inclination (10°) orbits with a perigee of 1.1 R_E, an apogee of 5.8 R_E, and a period of 9 hours.
- The Helium, Oxygen, Proton, and Electron (HOPE) mass spectrometer [*Funsten et al.*, 2013] in the Energetic Particle Composition and Thermal Plasma (ECT) suite [*Spence et al.*, 2013] measures electrons and ions in the energy range of ~1 eV-~50 keV and distinguishes composition of three major ion species, H^+, He^+, and O^+.

5. Ion Spectral Structures



Solar wind parameters during the geomagnetic storm on 2 Oct 2013. The shaded regions correspond to 5 orbits of Van Allen Probe A.

- Five whole orbits of Van Allen Probe A before, during, and after the geomagnetic storm.
- The top and middle panels show the measured and simulated H^+ energy flux, respectively. The bottom panel shows the simulated drift time to L=10.
- The simulations were carried out with the Weimer 1996 electric field model [*Weimer*, 1995] and a dipole magnetic field model.



A: Pre-storm. During the quiet geomagnetic conditions before the storm, Probe A measured **fine spectral structures**: two in the inbound pass and one in the outbound pass. The data-model discrepancy at low energies indicates that low-E H^+ do not exist at the injection boundary (L=10) in reality.

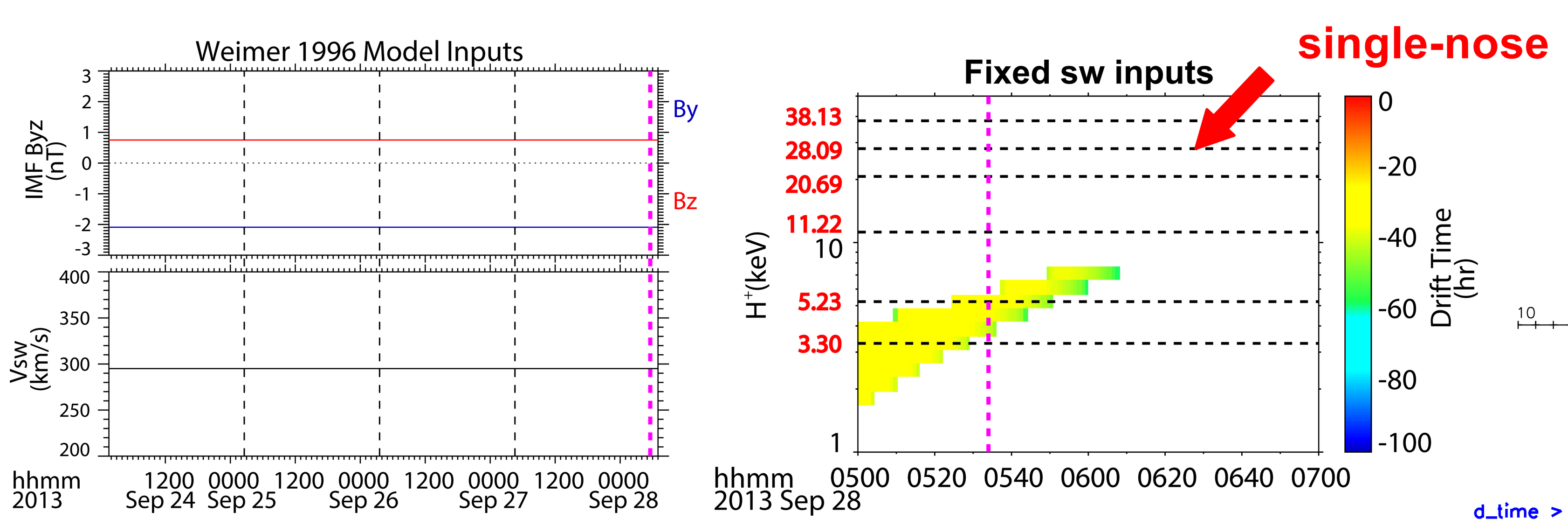
B: Main phase. The **newly injected plasma** can be noticed in the outbound pass. The model reproduced the **energy-dispersed injection**, although the deeper injection appears at a lower energy.

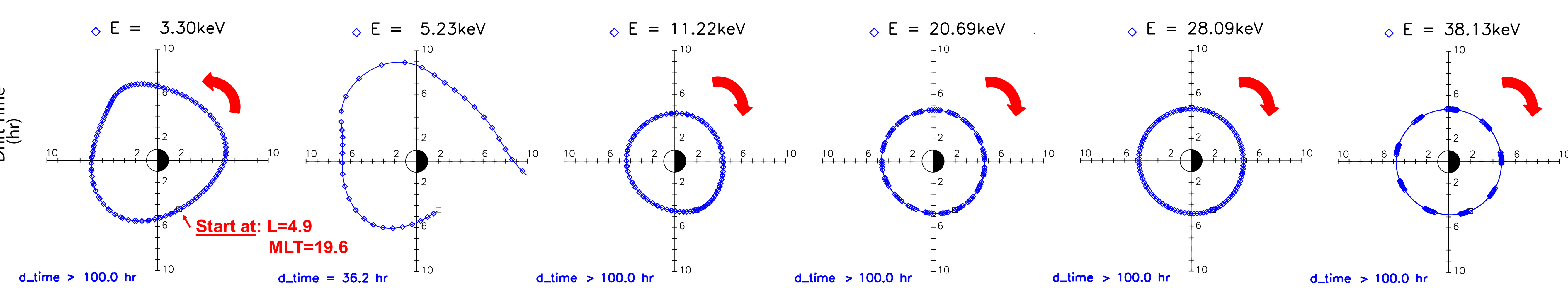
C: Early recovery. Following the injection of new plasma, the inner edge of the plasma sheet shows **only one nose** structure. The model reproduced the only nose present in both the inbound and outbound passes.

D: Early recovery. Spectral structures are simple, **without traces of nose structures** in the data spectrogram. The model predicts well the extent of penetration of the plasma.

E: Late recovery. As geomagnetic conditions become quieter after the storm, **fine spectral structures are visible once again** in the data spectrogram. The model reproduces the fine structures.

6. Formation of Single- and Multiple-Nose Structures

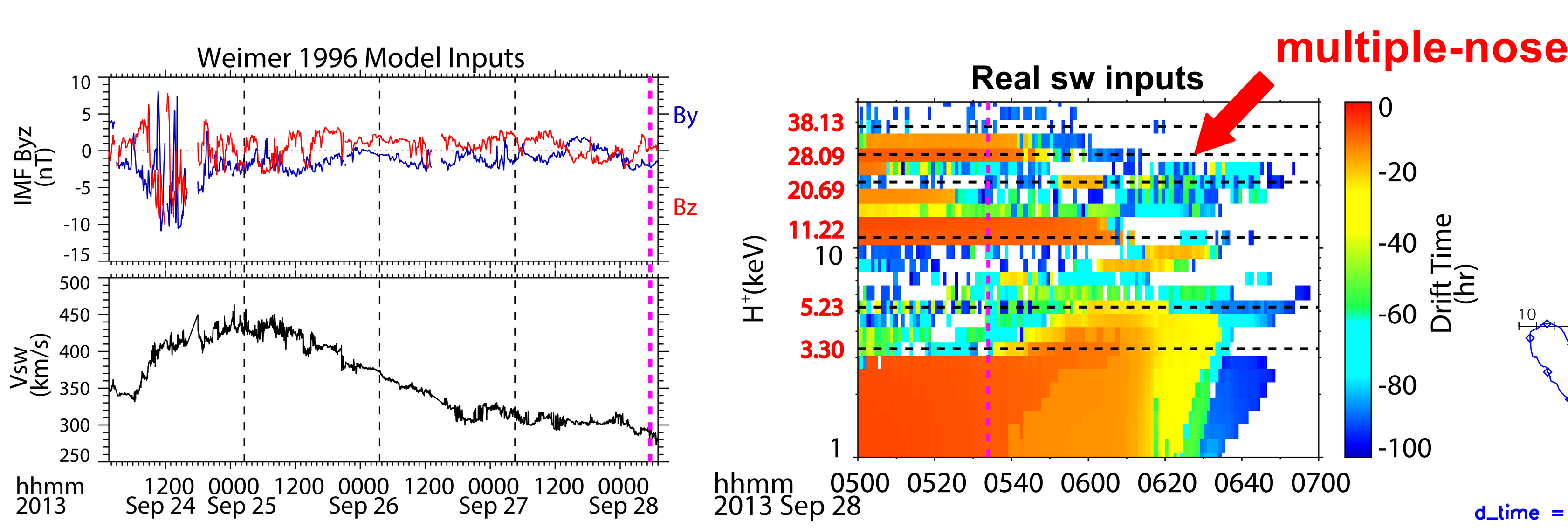


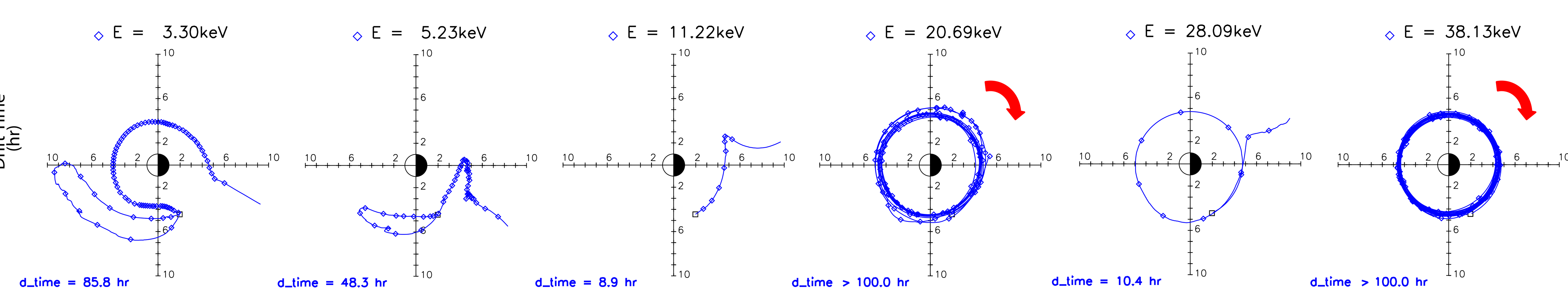


Fixed solar wind inputs:

- The model produces only one nose structure.
- Low-energy H^+ drift eastward around the Earth dominated by the ExB drift.
- High-energy H^+ drift westward around the Earth dominated by the gradient-curvature (GC) drift.
- **The nose occurs at energies for which the ExB and the GC drifts nearly cancel each other.**

d_time: drift time to L=10





Real solar wind inputs:

- The model produces several nose structures.
- The main nose at ~10 keV occurs for ions with direct access from the injection boundary.
- The secondary nose at ~28 keV occurs for ions which drift once around the Earth before reaching the observation site.
- **The time-varying solar wind parameters induce changes in the electric field which modifies the trajectories of ions allowing access to the observation site in multiple bands.**

7. Summary and Discussion

- A case study of the time evolution of **H^+ "nose-like" structures** observed by the ECT-HOPE instrument onboard Van Allen Probe A during the geomagnetic storm of 2 October 2013 has been performed.
- The characteristics of the H^+ spectral structures follow a **cyclic pattern over the storm**, that is, the observed features change dramatically as the storm starts and then returns to its initial pre-storm state:
  Pre-storm: Spectral features are characterized by fine nose structures centered at around 10 keV.
  Main phase: Deeper penetration occurs in a broader energy range.
  Early recovery: Simple nose structures begin to appear again.
  Late recovery phase: Fine nose structures are observed again.
- **Single-nose structures** are formed by ions with energies for which the ExB and gradient curvature drifts nearly cancel each other, allowing their deeper penetration than ions with lower and higher energies.
- **Multiple-nose structures** are associated with solar wind variations. They are formed by ions with different energies that drift different number of times around the Earth before reaching the observation site.

8. References

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9. Acknowledgements

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