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Ion spectral structures observed by the Van Allen Probes

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Abstract

During the last decades several missions have recorded the presence of dynamic spectral features of energetic ions in the inner magnetosphere. Previous studies have revealed single "nose-like" structures occurring alone and simultaneous nose-like structures (up to three). These ion structures are named after the characteristic shapes of energy bands or gaps in the energy-time spectrograms of *in situ* measured ion fluxes. They constitute the observational signatures of ion acceleration, transport, and loss in the global magnetosphere. The HOPE mass spectrometer onboard the Van Allen Probes measures energetic hydrogen, helium, and oxygen ions near the inner edge of the plasma sheet, where these ion structures are observed. We present a statistical study of nose-like structures, using 1-month measurements from the HOPE instrument. The results provide important details about the spatial distribution (dependence on geocentric distance), spectral features of the structures (e.g., characteristic energy and differences among species), and geomagnetic conditions under which these structures occur.

Motivation

- Present the results of a routine for the identification of "nose-like" structures.
- Report for the first time a statistical study of ion structures for three major ion species: H^+, He^+, and O^+, using 1-month measurements from the HOPE instrument onboard the Van Allen Probe A.
- Investigate the spatial distribution, spectral features of the structures (e.g., characteristic energy and differences among species), and geomagnetic activity under which these structures occur.

Introduction

- Over the last 30 years several magnetospheric missions have detected ion structures which when observed 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].
- Different types of nose structures have been observed and modeled: single noses [*Ganushkina et al.*, 2001], double noses [e.g., *Buzulukova et al.*, 2003], and triple noses [e.g., *Ebihara et al.*, 2004].
- 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.

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^+.

Nose Structures

Formation of nose structures

- As particles drift from the tail region into the inner magnetosphere approaching the Earth, they feel the antagonistic effects of the **ExB** drift (eastward, energy independent) and the **gradient–curvature** drift (westward, energy dependent) as shown in Figure 1a.
- As shown in Figure 1b, particles with **low energies** are dominated by the ExB drift and drift eastward on closed orbits (green trajectory), while particles with **high energies** are dominated by gradient-curvature drift and drift westward on closed orbits (red trajectory).
- Particles with energies within an **intermediate energy** band have open orbits. Particles with these energies are able to reach deep into the inner magnetosphere and form the nose structures.

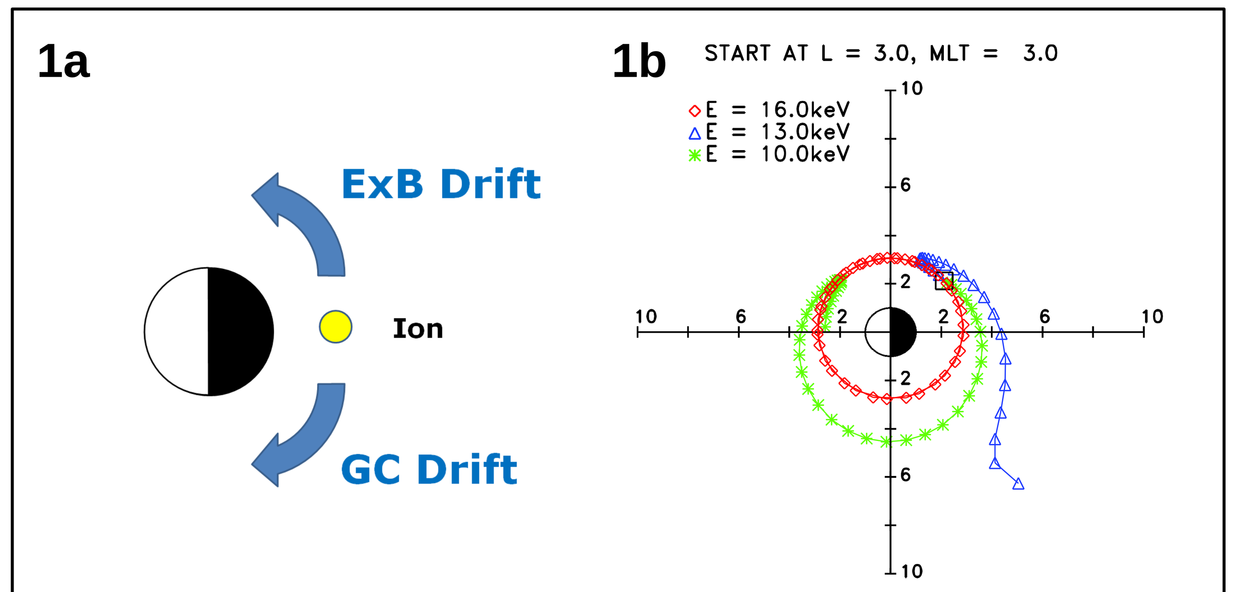


Fig. 1:
Two **opposing drifts** act upon ions entering the inner magnetosphere (Figure 1a). Backward **particle tracing** was performed using a Volland-Stern electric field model [*Volland*, 1973; *Stern*, 1974] and a dipole magnetic field for ions arriving at L=3, MLT=3 using Kp=2 (Figure 1b).

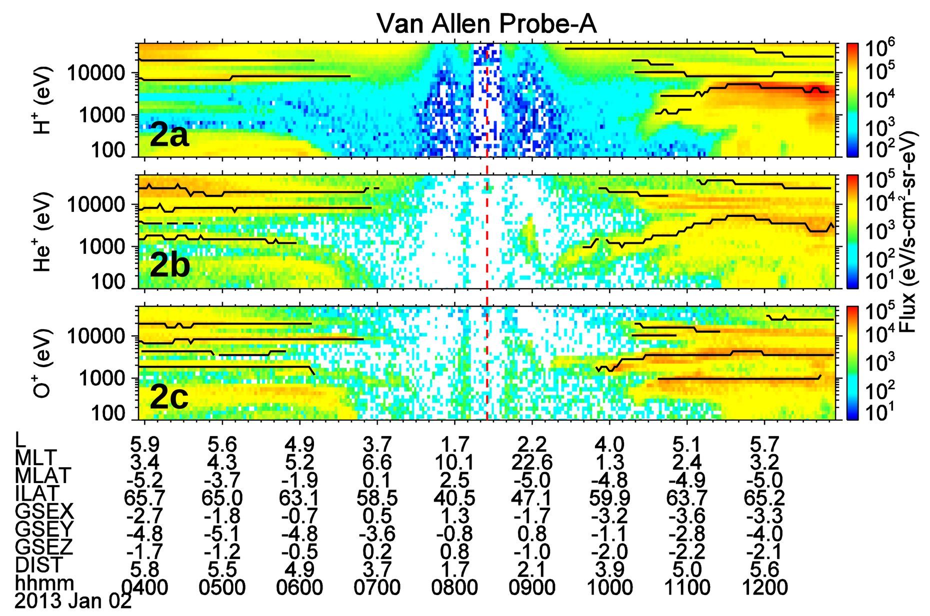


Fig. 2:
ECT-HOPE H^+, He^+, and O^+ energy-time spectrograms on the Van Allen Probe A during a whole orbit, centered at perigee (indicated by the vertical red dashed line), on 2 January 2013. The solid black lines show the nose structures detected by the Nose Identification Routine (NIR) on both the inbound and outbound passes.

Event Selection

- The short orbital period of the Van Allen Probes, allows it to survey the inner edge of the plasma sheet **several times a day** thus providing large amounts of data.
- The large number of data motivated the development of a **Nose Identification Routine (NIR)** that automatically detects the nose structures in the energy-time spectrograms and provides their spectral features.
- The NIR's basic procedure is to find the **flux maxima** in the time period of the spectrogram and their respective energies. It then traces these energies from the outbound towards perigee and stops when the flux drops below a given flux threshold.
- Ion data over a period of **one month** (January 2013) allowed to analyze a total of **166** inner magnetosphere crossings (inbound and outbound passes). Only structures with energy above 1 keV were considered. From these crossings the NIR successfully detected the nose structures in:
  - 113 H^+ events
  - 110 He^+ events
  - 94 O^+ events

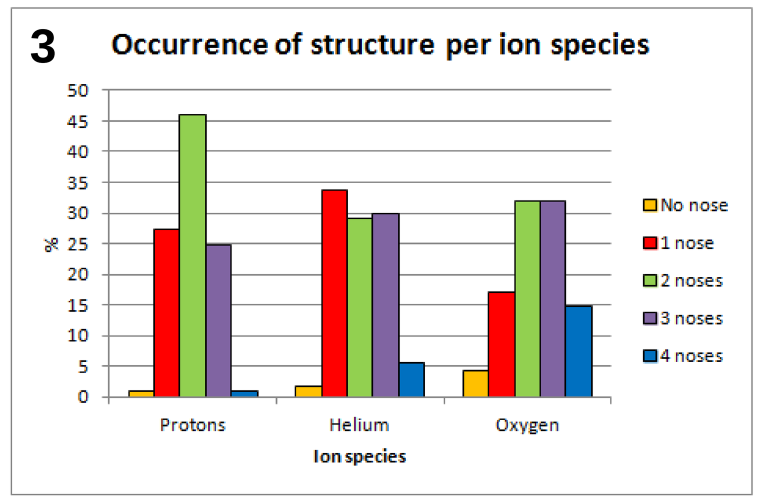
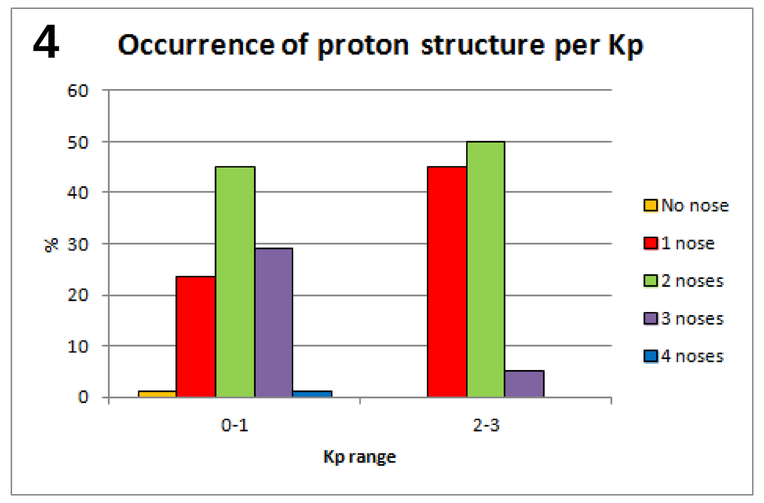
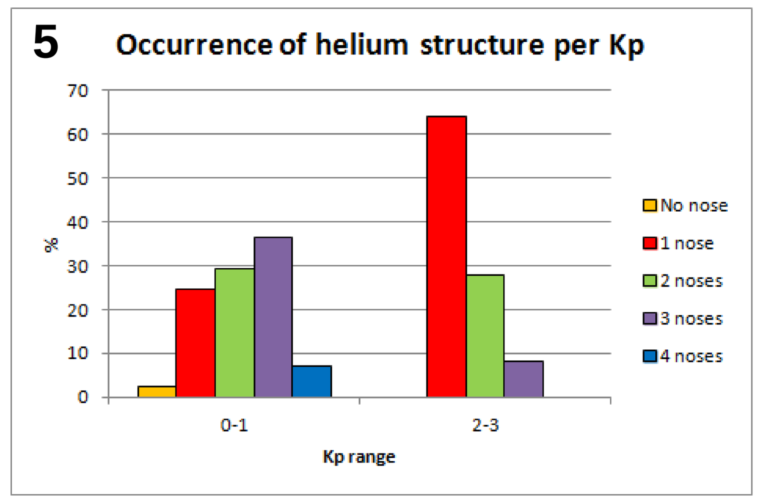
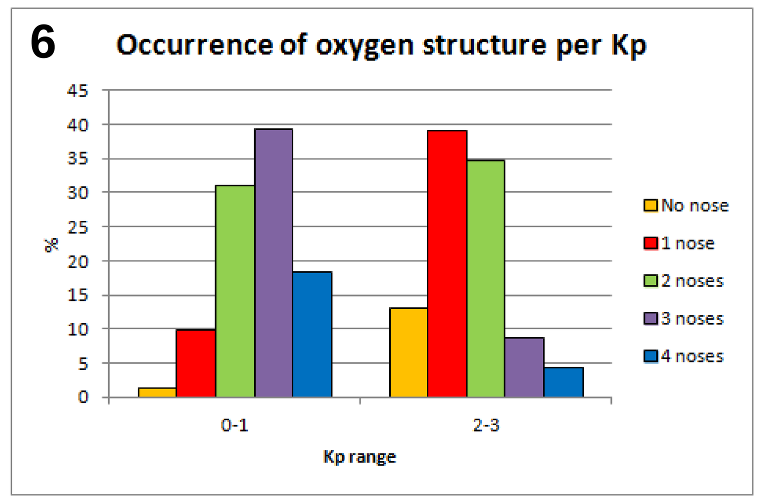


Fig. 3:
- Plotted is the normalized occurrence of the **number of energy structures per ion species**. A distinction has been made between events presenting no nose structure (orange), one nose (red), two noses (green), three noses (purple), or four noses (blue).
- Four-nose structures are **more frequent in the heavy ions** than in the protons.







Figs. 4-6:
- Each figure shows the normalized occurrence of the **number of energy structures per *Kp* index range**, for the different ion species. A distinction has been made between events presenting no nose structure (orange), one nose (red), two noses (green), three noses (purple), or four noses (blue).
- Regardless of ion species, three- and four-nose structures are **more frequently observed during quiet times** (*Kp*=0-1).

Distribution of Events

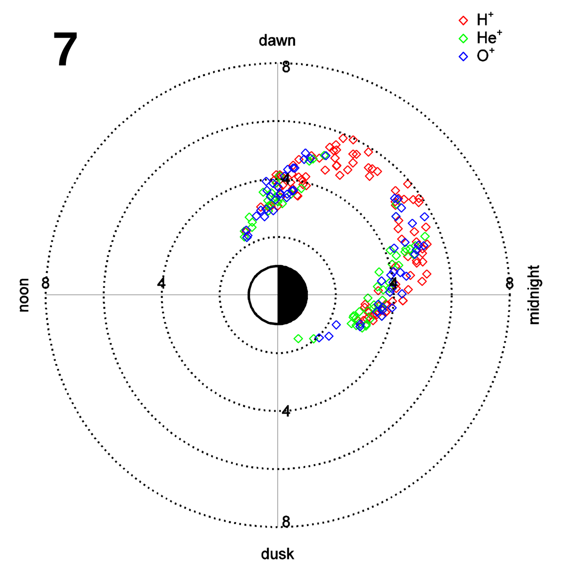


Fig. 7:
A TS04D geomagnetic model was used.
- Plotted are the events were **two noses** were observed.
- The **heavy-ion structures** in general **penetrate deeper** than the proton structures.
- Percentage of structures that penetrate deeper than L=4:
  - H^+: 38%
  - He^+: 75%
  - O^+: 58%

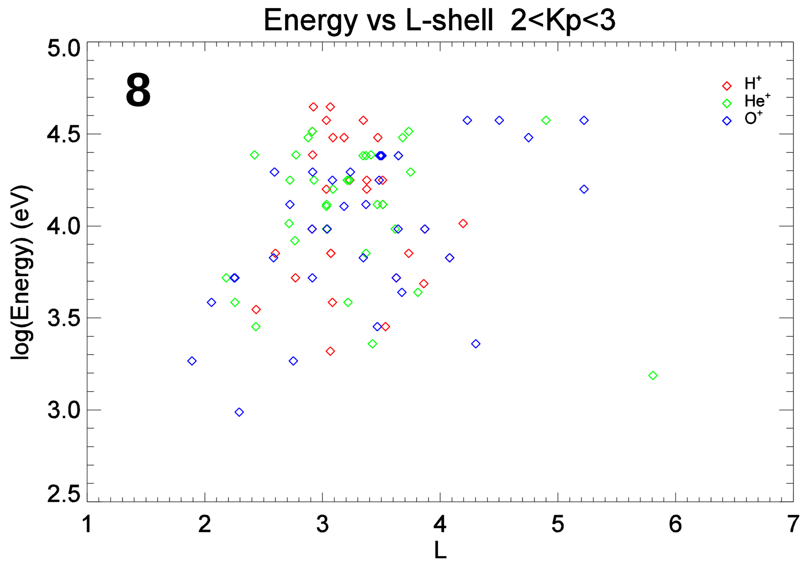


Fig. 8:
- Energy vs L-shell of the nose tip for the three ion species during moderately active times (*Kp*=2-3).
- For all species, nose structures that reach deeper have **lower energies**.

	1 keV	10 keV	20 keV
H^+	22.7 hr	11.4 hr	12.4 hr
O^+	145.9 hr	64.5 hr	49.6 hr
He^+	4129.8 hr	311.9 hr	156.1 hr

Table 1:
Charge exchange lifetimes for the three ion species (H^+, O^+, and He^+) at L=4 as presented by *Smith and Bewtra* [1978].

Summary and Discussion

- For the first time, a statistical study of **"nose-like" structures** in the spectrograms of three major magnetospheric ion species, namely H^+, He^+, and O^+, observed by the ECT-HOPE instrument onboard Van Allen Probe A has been reported.
- The large amount of data provided by the Van Allen Probes motivated the development of a **Nose Identification Routine** (NIR) which detects automatically the nose structures and provides their spectral features.
- Multiple-nose events (3 and 4 noses) are more frequently observed during **quiet times** possibly because during these times nose structures are able to overlap and become more dynamic, while during more active times particle injections penetrate deep wiping out the previously formed structures. They are also more frequently observed in the heavy ions probably due to effects of **charge exchange lifetimes**.
- The L-shell dependence of the energy of the nose tip is consistent with the energies of **particles drifting from the tail plasma sheet** and with losses expected due to **charge exchange** with the atmospheric neutral hydrogen.
- Future work includes improving the NIR, expanding the time covered by this study, and extending the statistical study to other missions like THEMIS and Cluster.

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Acknowledgements

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