Heavy ion dominance near Cluster perigees

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Abstract

Even though studies in the past stated that protons were the dominant species in the Earth's ring current, it is now well known from studies that there is presence of measurable and appreciable quantities of oxygen and helium ions as well as protons. Signatures of heavy ion dominance over protons were observed by Cluster (CIS-CODIF) around some of its perigee passes. In the present work we do a statistical study of these events and examine their spatial and temporal distributions. We interpret the data in light of the charge exchange mechanism of ion phenomena. To do so we calculate the ion drift trajectories backwards in time and test our results qualitatively by estimating the charge exchange loss of ions with ion drift time as they are injected into the inner magnetosphere.

Motivation

- Report a statistical study of heavy-ion dominant events in the lower L-shell regions observed by Cluster in some of its perigee passes.
- Examine the spatial and temporal distribution of these events and propose a mechanism that explains the distribution features.

Introduction

- Measurements of particle energy spectra in the inner magnetosphere have been found consistent with trajectories resulting from the interplay between particles and electric and magnetic fields that carry plasma sheet ions to the low L-value regions [*Smith and Hoffman, 1974; Ejiri, 1978*].
- In the regions of low L values the neutral hydrogen density is large enough to make the charge exchange decay mechanism a significant one [*Dessler and Parker, 1959; Kistler et al., 1998*].
- The charge exchange lifetimes depend on energy, L-value, species, etc. Heavy ions (O^+ and He^+) have longer charge exchange lifetimes than H^+ in the inner magnetosphere [*Smith and Bewtra, 1978*].
- Heavy-ion dominant events have been reported in the L≲3.5 region [*Lundin et al., 1980; Kistler et al., 1998*].

Instrumentation

- The Cluster mission (2001-present) consists of four identical spacecraft in elliptical polar orbits with a period of ~57 h and with perigee in the range 1-4 Earth radii (R_E).
- Over the course of one year the precession of Cluster's orbit allows each spacecraft to cover all local times.
- In this study we use plasma observations from the Composition Distribution Function (*CODIF*) instrument [*Möbius et al., 1998*], which is part of the Cluster Ion Spectrometry (*CIS*) experiment, and measures the complete three-dimensional distributions of the major magnetospheric ions, H^+, He^+, and O^+, over an energy per charge range between 0.04 and 40 keV/e.

Heavy-Ion Dominant Events

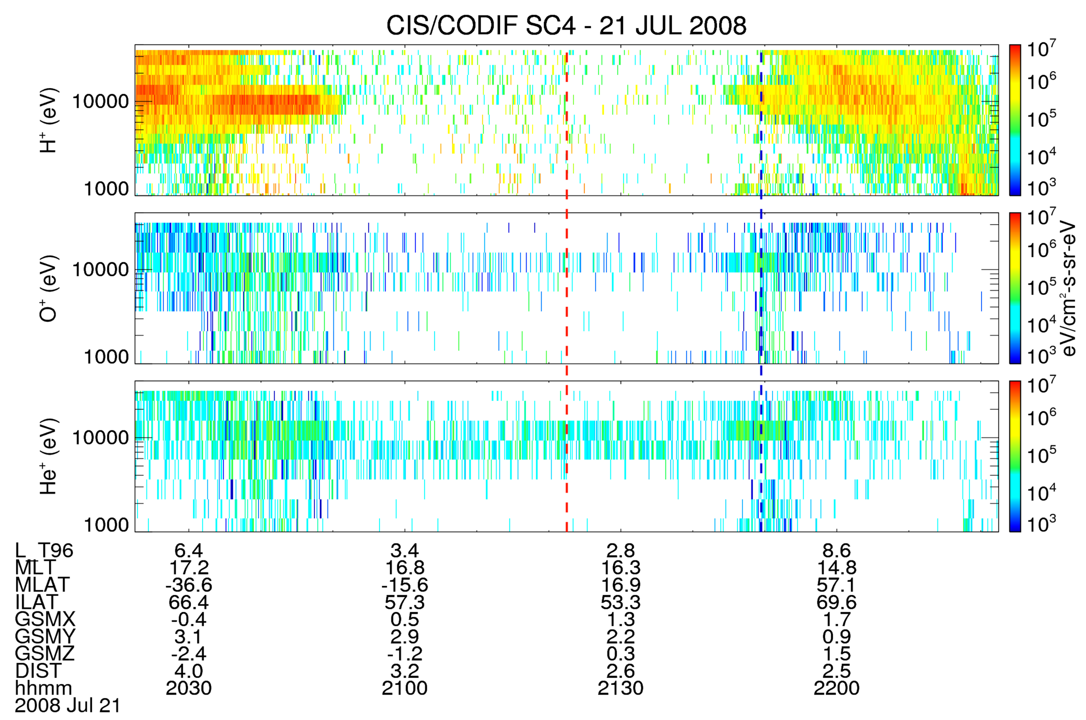
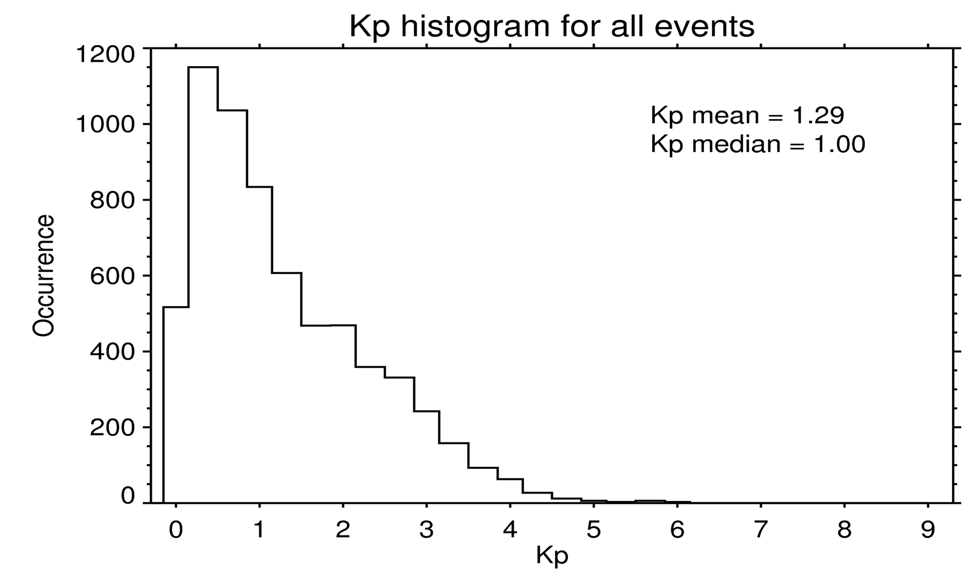


Fig. 1:
He^+ dominant event on 21 July, 2008. The H^+ spectrogram shows that no proton structure penetrates deeper than ~L=4, while the O^+ and He^+ spectrograms show that the heavy ions drift to the minimum L-value at around 10 keV (although O^+ in a much weaker fashion).

Fig. 2:
Plotted are the Kp indices for the 48 hours prior to every event. The low mean and median values indicate that the events occurred during relatively **quiet times**.

Event Selection

- The event selection was carried out by visually inspecting the H^+, He^+, and O^+ energy-time differential flux spectrograms.
- Events occur when hot He^+ or O^+, or both, present structures that **drift deeper** than the hot H^+ structure at the same energy. The dominant species is the one with **higher flux**.
- A total of **133 events** were observed:
  1. 45 where He^+ was dominant
  2. 5 where O^+ was dominant
  3. 83 where both heavy ions were equally dominant



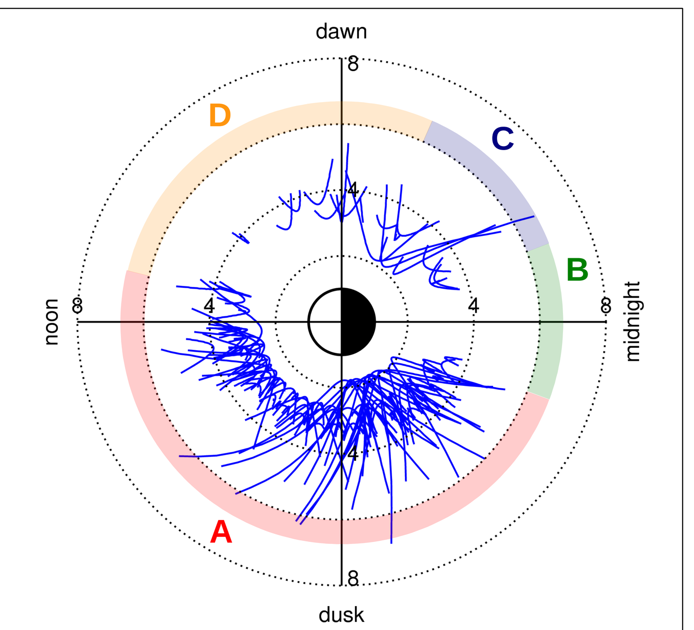
Distributions

Temporal distribution
Cluster spacecraft 4 CIS/CODIF data was analyzed for the years **2001-2011**;

- Mar 2001–Aug 2006: **No observed events** probably due to a higher minimum L-value (L>4)
- Sep 2006–Jun 2009: **Identified heavy-ion dominant events**
- Jul 2009–Dec 2011: **No data** (changes in the CIS/CODIF operation)

Spatial distribution (Fig. 3) A T96 geomag. model was used, [*Tsyganenko, 1995*]

- Great concentration of events in the MLT=11-22 hours **(Sector A)**
- No events occurred in the MLT=22-2 hours **(Sector B)**
- Small concentration of events in the MLT=2-4 hours **(Sector C)**
- Almost no events in the MLT=4-11 hours **(Sector D)**



Summary and Discussion

- A statistical study of heavy-ion dominant events observed by the CIS/CODIF instrument onboard Cluster has been reported. Of particular interest is the spatial distribution of these events.
- Given the relatively long drift times charge exchange is expected to play an important role in the particle loss process. Because the charge exchange lifetimes are species and energy dependent we would expect that H^+ would be lost at a faster rate than the heavy ions.
- Charge exchange decay is found to explain the spatial distribution for most of the events.
  - **Sector A**: The drift times seem to be **long enough** as to allow the protons to disappear almost completely leaving the heavy ions as the dominant species. Also, in this sector the lower L-shell regions are accessible to particles with a **wider range** of energies.
  - **Sector B**: The absence of events might be due, in part, to the instrument being turned off some years during eclipse. In addition, this absence is not clearly explained by the results in this study probably because of the failure of the electric field model used herein to accurately reproduce the trajectories in this region. However, these observations are in agreement with previous studies [*Zhang et al., 2008, 2009*] which have shown that energetic ions do not drift along the **midnight meridian** due to the effect of gradient-curvature drift and they follow paths that are **tilted** toward the pre-midnight sector of the inner magnetosphere.
  - **Sector C**: The species relative abundances are similar to those in the dusk sector. However, the **slightly longer** drift times and **narrower** energy bands may account for the smaller concentration of events.
  - **Sector D**: The absence of events might be due to the **long drift times** which allow for the decay of not just protons but also He^+ and O^+. Furthermore, **narrower** energy bands can access the lower L-shell regions in this sector compared to the afternoon hours.
- Future work includes comparing the simulated species abundance ratios with the data, and doing a similar statistical study using Van Allen Probes data.

Bounced-averaged Particle Trajectories

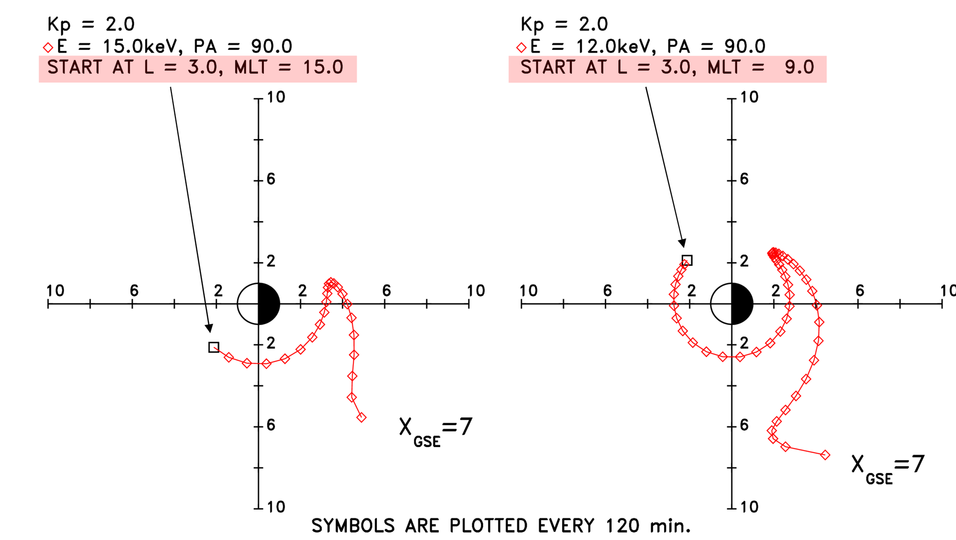


Fig. 4:
Backward particle tracing was performed using a Volland-Stern electric field model [*Volland, 1973; Stern, 1974*] and a dipole magnetic field for ions arriving at L=3 for all local times in 1 hour intervals, using Kp=2.

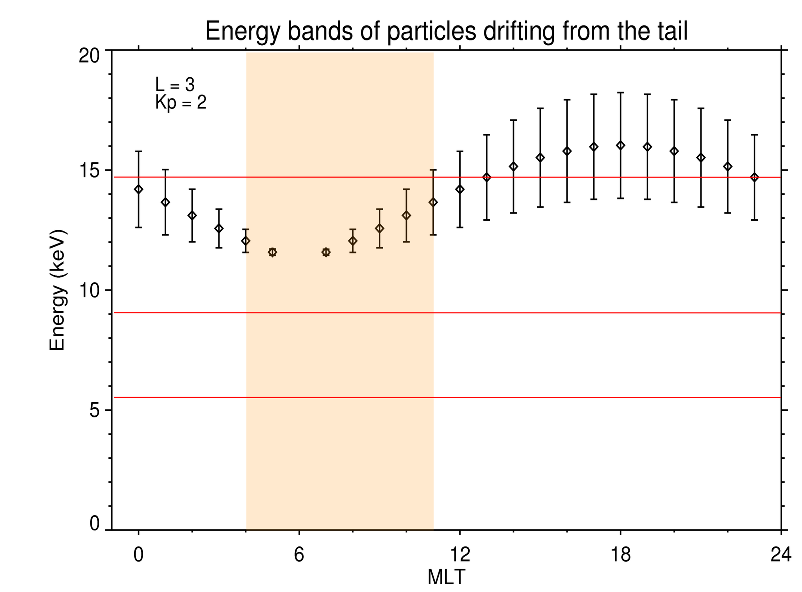


Fig. 5:
The morning hours, particularly Sector D (shaded region) which is where almost no events are observed, show **narrower energy bands** (no particles reach MLT=6), compared to those in the evening side. The red horizontal lines indicate the limits of three CIS/CODIF energy channels.

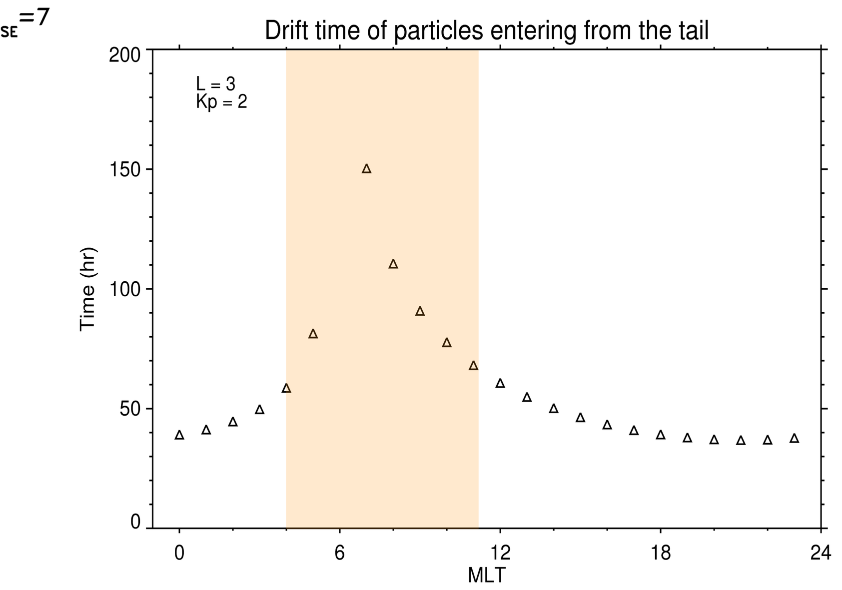
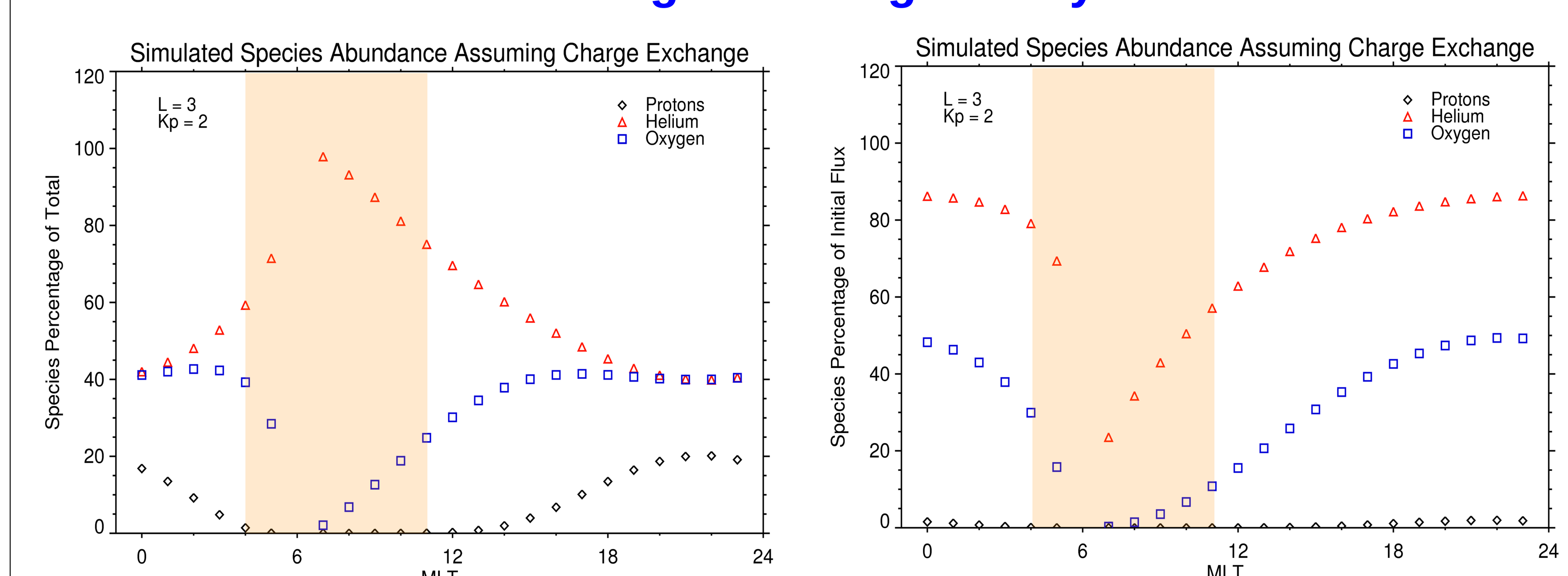


Fig. 6:

- Particles take at least ~2 days to drift to L=3, making these particles strongly **subject to charge exchange** effects.
- The **drift times peak** around dawn and gradually decrease toward the early morning and evening sectors.
- The **long drift times** in Sector D can explain the absence of events.

Charge Exchange Decay



Figs. 7 & 8:

- The charge exchange decay was calculated using an **initial** (X_{GSE}=7) **flux population** of 89% H^+, 4% He^+, and 7% O^+. This abundances were estimated using correlations of magnetospheric ion composition with solar activity [*Young et al., 1982*].
- While He^+ is the **most abundant** species at all MLT, this is more accentuated around MLT=6.
- Even though Sector D is highly He^+-dominant all species show their **lowest fluxes** in this region.

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