Observations of Ion Populations from the KiNET-X Sounding Rocket Mission

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Abstract

The Kinetic-scale energy & momentum transport experiment (KiNET-X) investigated kinetic-scale ionospheric plasma transport for a known input energy & momentum by measuring ionospheric perturbations near sounding rocket barium releases. The diagnostic main payload of the rocket, launched May 2021 from Wallops, included an array of eight Petite-Ion-Probes (PIPs), two pairs of orthogonal DC/AC electric field probes and two Electron Retarding Potential Analyzers (ERPAs). Two subpayloads (PIP-Bobs), each carrying two PIPs, were released from the main structure during the initial phase of the flight, forming a line of spatially distributed instruments along the along-ram, perp-B direction. Also, two ground stations and one aircraft made optical measurements of the two barium clouds with video and DSLR cameras.

The PIPs are retarding potential analyzers that measure the thermal ion flux spectrum, combining both oxygen and barium. Extracting scalar plasma parameters from PIP data via forward-modeling requires a reasonable model of the plasma environment. Both the charged payload potential estimated from the ERPAs' measured electron temperature and the geophysical plasma flow velocity derived from the DC electric field (DCE) probes were incorporated in an improved model of the PIP measured current in a multi-species modified Maxwellian plasma. The resulting oxygen ion temperatures, and ratios of injected (barium) plasma density to ambient (oxygen) plasma density, from this improved PIP data analysis exhibited several features of interest. For this presentation, we will focus on the PIP-measured barium ion densities. The PIPs measured a much higher barium density peak value following the second barium release than following the first one. However, ground-based optical data suggested that the net barium ion yields were approximately the same for the two releases. Additionally, the PIPs observed a faster decay of barium density for the second release compared to the first one. In order to determine if these features could be described by a straightforward plasma physics model, we created a simple particle-trace model of the evolution of ion clouds, ionized at different times, in a static geomagnetic field, with only the magnetic force acting on the moving ions. The following assumptions were made for each ion cloud: (1) the neutral gas's initial expansion velocity directions and thus, spatial distribution, followed a Gaussian distribution; (2) prior to the cloud's specific ionization time, the neutral cloud expanded with a set radial expansion velocity as well as drifted along with the RAM velocity of the main payload; (3) the number of ions in an ion cloud varied based on the time of ionization. The number of ions produced at each selected ionization time were determined from camera measurements of the number of ions over time following the first barium release. Combining these ion clouds with our knowledge of the positions and look-directions of our PIPs, we estimate the Ba ion densities that our PIPs would observe in such a cloud. We present comparisons of the measured barium ion density to this simple-kinetics-model particle-tracer-estimated density and discuss observed disparities from this simple model.

Introduction

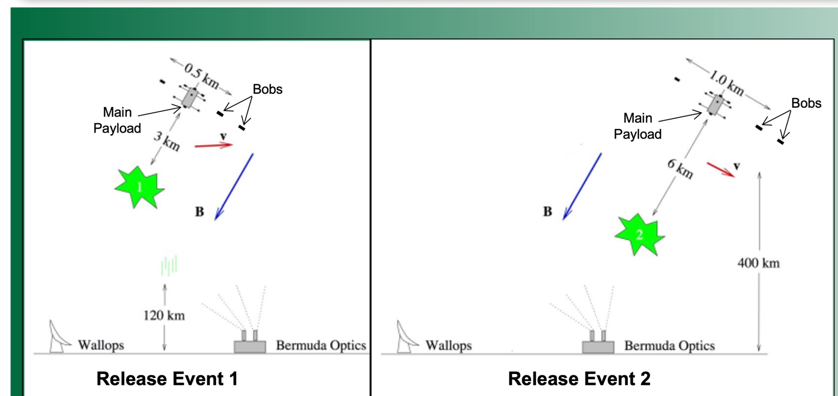

Figure 1. KiNET-X instrumentation & release geometry. (Modified version of figure from P. Delamere.)

KiNET-X Mission Description

- Goal: Investigate kinetic-scale ionospheric plasma transport for a known input energy & momentum
- The KiNET-X sounding rocket launched from Wallops in May 2021
- During the descent phase, the rocket made two barium releases which were measured by instruments onboard the main payload, onboard two deployed instrument packages and on the ground.

Initial Observations

Observations of Both Releases

- Increases in electron temperature (T_e) up to about 2-3x the initial value *(Delamere, et. al., 2024, in prep)*
- The measured ratio of the DC electric and magnetic fields' magnitudes was on the order of the ambient Alfvén speed value *(Delamere, et. al., 2024 , in prep).*
- Increase in ambient O+ plasma temperature (Fig. 2)

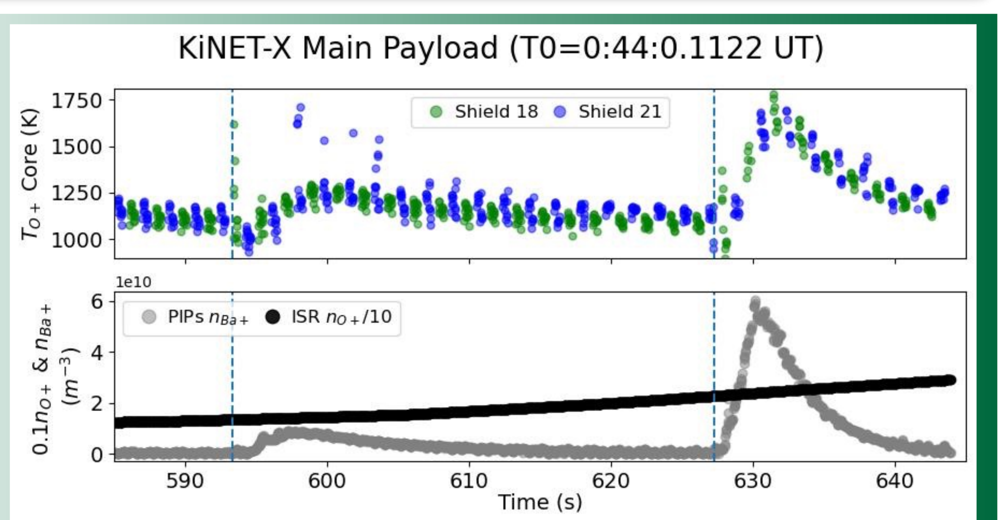

Figure 2. PIP-measured O+ temperature data (top) and PIP-measured Ba+ density along with MLH ISR O+ density (bottom), with releases indicated with dashed lines.

Observations Unique to Second Release

- A strong electron beam was observed about 1s after the second release *(Delamere, et. al., 2024 , in prep).*
- Observed greater fluctuations in the measured DCE and magnetic fields after the second release *(Delamere, et. al., 2024 , in prep).*
- PIPs observed larger ambient O+ temperature increase and larger Ba+ density following the second release as shown in Figure 2.
- PIPs observed barium ions much earlier after the second release than after the first.

Science Focus: Skidding or Not?

Key Results from the KiNET-X Mission

- Alfvénic disturbance in the first few 100ms after releases *(Delamere, et. al., 2024 , in prep)*
- Substantial wave-particle interactions observed *(Delamere, et. al., 2024 , in prep)*

Skidding Signatures in Thermal Ions?

- After the second release, the field-aligned electron beam and associated strong parallel electric fields indicate skidding may have occurred *(Delamere, et. al., 2024 , in prep).*
- Questions to answer
  - Does skidding occur in either event?
  - If so, for how long did the ion cloud skid?
- Method: Compare observed barium densities with those generated by a particle tracer model

Ion Density Analysis

Model Overview

- Assume barium neutrals radially expand from a drifting point source location.
- Model trajectories of barium ions, created at various times from photoionization of these neutrals, moving under the Lorentz force as illustrated by the zoomed in plot of Figure 4.
- Skidding can be added to the model, represented by a delay to the onset of gyromotion in radial expansion.
- Estimate model density by calculating the ion densities within the region of the main payload as illustrated in the plots of Figure 5.
  - Can also impose FOV constraints
- The neutral cloud expansion velocity and time-dependent ionization profile were derived from optical observations of the barium cloud following the first release.
  - No such observations exist for for the second release
- Assumptions for release 2 model
  - Use the time-dependent ionization profile from release 1
  - Expansion velocity (v_{exp}) is greater than that of release 1 based on PIP observations.

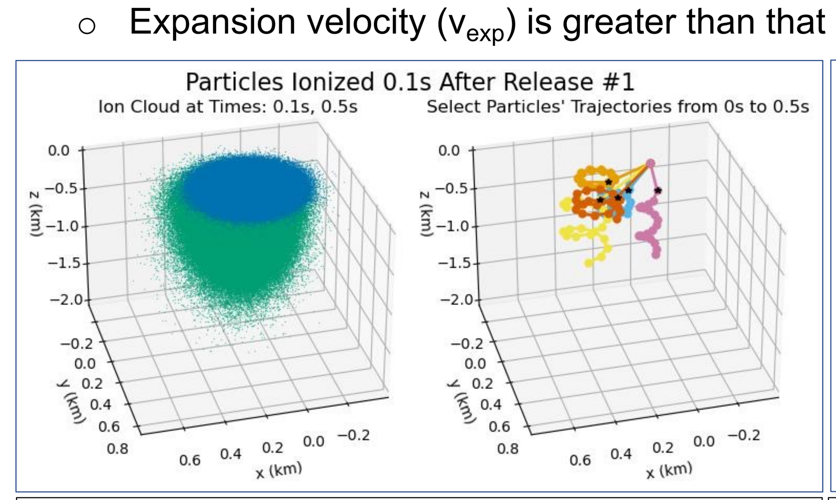

Figure 4. (Left) Cloud ionized at 0.1s plotted at 0.1s (blue) and 0.5s (green). (Right) Select particles' trajectories and ionization points (black stars). Note: small axes scales used to show trajectories' details.

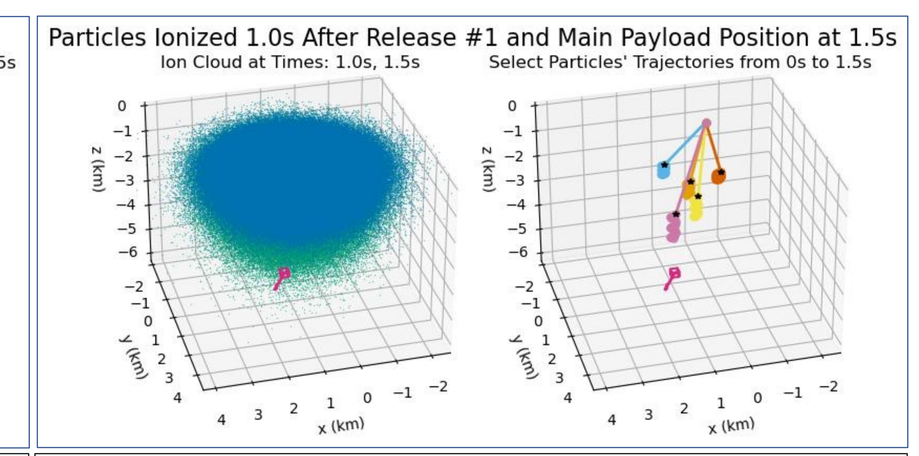

Figure 5. Main payload's "measurement region" (box) and RAM vector are plotted on both subplots in magenta. (Left) Cloud ionized at 1s plotted at 1s (blue) and 1.5s (green). (Right) Select particles' trajectories and ionization points (black stars).

No-Skidding Model Results

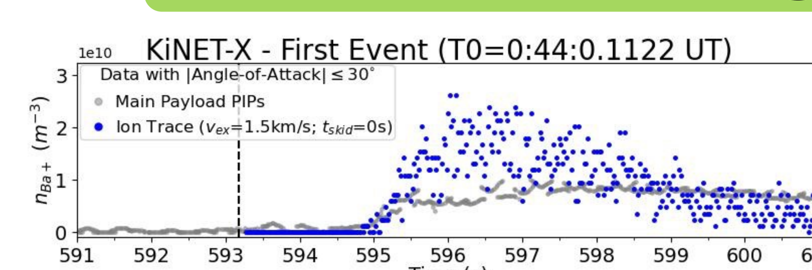

Figure 6. Comparison of modeled density to measured density for the first release, the time of which is indicated by the dashed line.

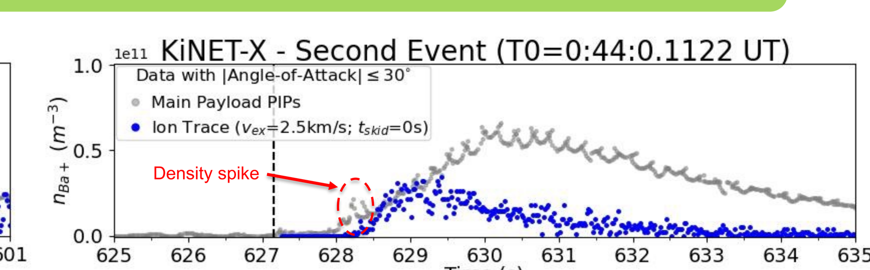

Figure 7. Comparison of modeled density to measured density for the second release, the time of which is indicated by the dashed line.

- Model results for the first release closely match the time of first Ba+ observation and the observed time of peak n_{Ba+} as seen in Figure 6.
- The model of the second release (Fig. 7) does not follow the observations as closely.
  - Settled on the expansion velocity (v_{exp}) by comparing model results with different v_{exp} values
  - A slight difference in the onset of the density increase between the modeled and measured data
  - A spike in the measured n_{Ba+} (highlighted in Fig.7), right after 628s, is not captured by the model.
  - The model's Ba+ density slope during the onset phase and time of peak n_{Ba+} do not match the measured data.

Add Skidding to Release 2 Model

- Comparing the model results for different skidding durations in Figure 8:
  - skidding adds a spike in density at the onset of the event
  - as t_{skid} is increased, this spike occurs later and increases in magnitude
- The model with t_{skid} =0.5s most closely resembles the observed spike, qualitatively.
- There is still a slight time offset between the observed and modeled data as well as a difference in the shapes of the two profiles
  - possible difference in the ionization profile of release 2

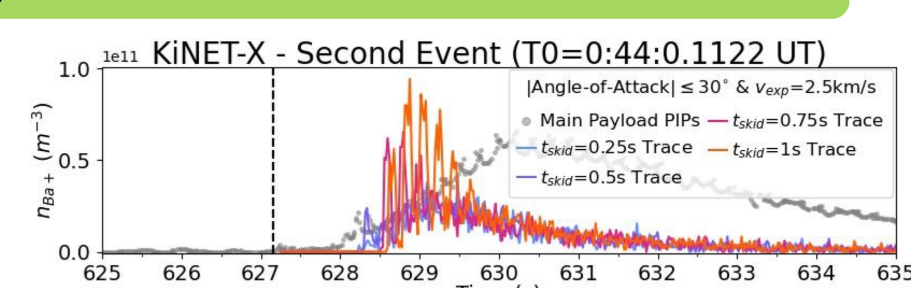

Figure 8. Comparison of model results for various skidding times and measured data, with release time indicated by the dashed line.

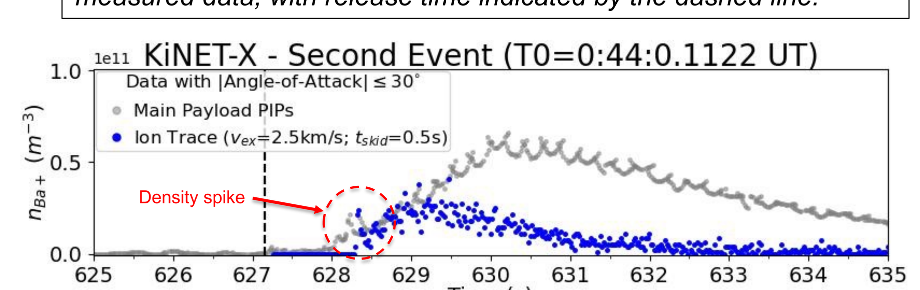

Figure 9. Comparison of modeled density with t_{skid}=0.5s to measured density following release 2 (dashed line). Red circle highlights n_{Ba+} spike.

Discussion/Conclusions

Skidding Conclusions

- Event 1 is well described by our simple particle trace model without skidding.
- Following release 2, main payload PIPs observed a spike in density coinciding with the observed strong electron beam (Fig. 10).
  - No n_{Ba+} spike or electron beam observed for event 1.
- Addition of a 0.5s skidding period to our model of release 2 produced a qualitatively similar spike in the n_{Ba+} profile to that observed by the PIPs

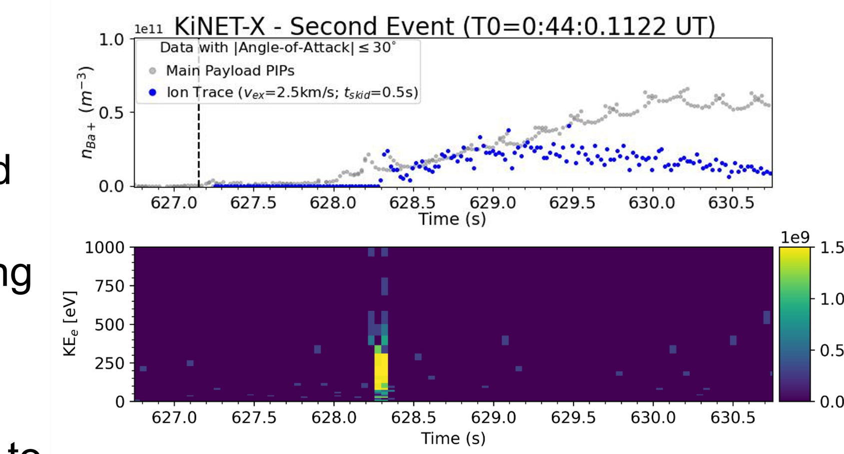

Figure 10. (Top) Plot of measured and modeled Ba+ zoomed in to the period just after release (dashed line). (Bottom) Field-aligned electron energy spectra (EPLAS) from (Delamere, et. al., 2024 , in prep). Note that the T0 used for the EPLAS plot may be offset from that used in the top plot by -0.1122s.

- Conclusions:
  - Skidding did not occur following the 1st barium release
  - Skidding likely occurred for ~0.5s or so following the 2nd barium release
  - May support the possibility that the observed electron beam was unique to event 2, not a consequence of misalignment of the phenomena and instrument.

Ambient Ion Heating

- PIPs observed changes in ambient O+ temperature
  - Event 1: ΔT_{O+}~150K
  - Event 2: ΔT_{O+}~500-600K
- Onboard E-field probe (Rob Pfaff, GSFC) data from event 2 (Fig. 11) shows Cyclotron and Lower Hybrid wave signatures in the time period of interest.
  - O+ Cyclotron Oscillations: $\omega_{c,O+}$~239.5 rad/s $\rightarrow$ $f_{c,O+}$~38 Hz
  - O+ Lower Hybrid Waves: $\omega_{LH,O+}$~4x10^4 rad/s $\rightarrow$ $f_{LH,O+}$~6334 Hz
- Calculated ΔT_{O+} due to the observed waves (Chang et al., 1986; Bell et al., 1991):
  - Cyclotron: 263K ≤ ΔT_{O+} ≤ 834K
  - Lower-Hybrid: ΔT_{O+} ≤ 43.7K
- **Conclusion:** Cyclotron heating is the most probable mechanism behind the observed ambient ion heating following the 2nd release.

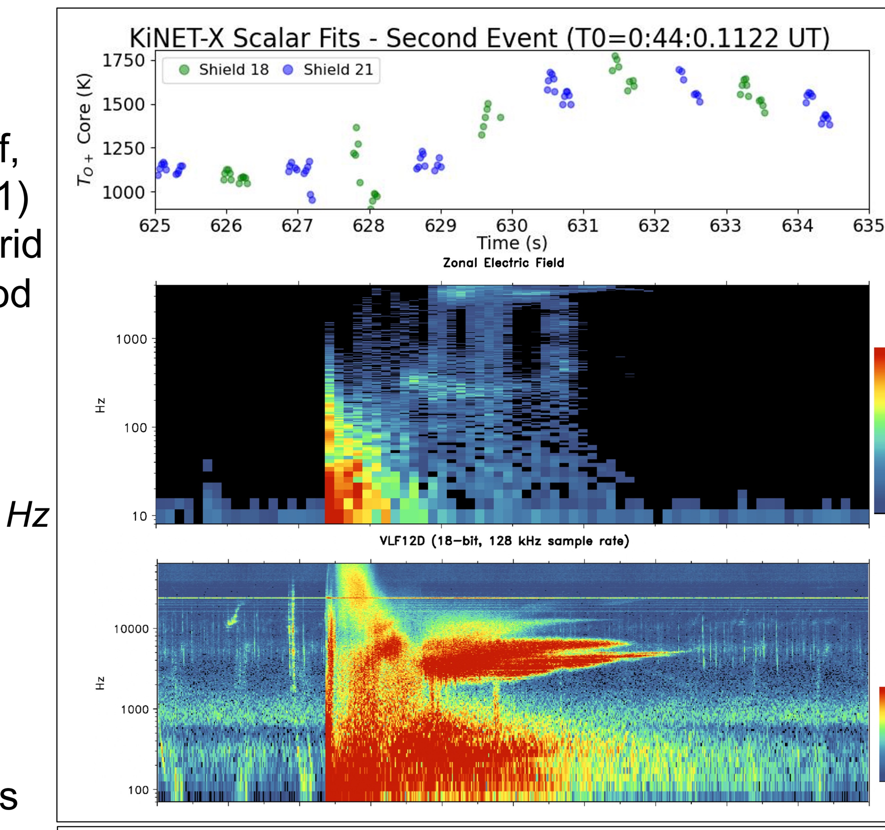

Figure 11. (Top) Main payload PIPs' observed temperature of excited O+ population. (Middle) Spectrogram of electric field waves for 10Hz to 4kHz. (Bottom) Spectrogram of electric field waves for 100Hz to 60kHz.

Remaining Work

- Multi-point analysis using the PIP-Bobs with the particle trace model
- Attempt to find a better ionization profile for event 2 using the particle trace model.
- Perform the same analysis of the E-field probe data for the 1st release to determine if the observed heating was due to the same wave-particle interactions as the 2nd event.

Acknowledgments

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