MMS Observations of Charge State and Mass Dependent Energization of Heavy Ions During Injections in the Earth’s Magnetotail

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**Ion composition and charge state during injections**

Understanding charge state and mass composition are important for understanding the energization and source of the plasma sheet.

Often, we assume protons are always the dominant species in the plasma sheet, and that “all-ion” type observations (which do not distinguish mass composition) are primarily protons at all energies.

However, observations have shown helium and oxygen are often dominant ion species over H\(^+\) in plasma sheet at highly suprathermal energies (e.g. Mitchell et al., 2018 JGR; Cohen et al., 2017 JGR; Kronberg et al., 2015 JGR).

Requires an explanation for species dependent energization – is it mass dependent effects (e.g. Speiser trajectories [Nosé 2001 JGR], “pick-up” energization [Delcourt 1994 JGR])? Or simply a higher charge-state [Möbius 1987 magnetotail phys]?

Most recent missions (e.g. Cluster, RBSP, MMS) do not directly measure charge state for ions w/ E > 40 keV/q

i.e. 200 keV O\(^{6+}\) and 200 keV O\(^+\) both register as 200 keV oxygen in time-of-flight/solid-state-detector systems.

Cohen et al. (2017) JGR
Ion composition and charge state during injections

Need a way to infer heavy ion charge state!

W/ RBSP-RBSPICE injection observations (inside 6 $R_E$), Mitchell et al. (2018) used correlation of flux, at different energies to infer the heavy ion charge state

Bounce-averaged guiding center particle motion is dependent on energy/charge

$$\frac{dx}{dt} = v_{EB} + \frac{KE_1}{q}v_{gc},$$

If no mass-dependent effects, ion trajectories and energization is charge-state dependent

By calculating the correlation coefficient between flux of each energy channel for different species, ridges of correlation could reveal the charge state. i.e. strong correlation where $E_{\text{heavy}} = (\text{heavy charge state})E_{H^+}$

How well does this hold up deeper in the tail?

Showing 4 examples of observations from MMS, which are representative of 4 types of cases we observe from a larger body injections

RBSP observations, Helium reaches higher E than H+

H$^+$ and He have E dispersions in flux, 236 keV He lines up well with 121 keV H$^+$, 182 keV He does not line up as well w/ 180 keV H$^+$

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Figures from Mitchell et al. (2018) JGR
Substorm (\(AE \approx 500 \text{ nT}\)) flows observed by MMS concurrent w/ energetic ion enhancements

He and Oxygen register fluxes at much higher energies than protons

From corr table: Ion fluxes well-correlated indicating He is He\(^{2+}\), and O is O\(^{5+}\) for E>~200 keV

He and O reach higher energies than H\(^+\) (>300 keV), due to higher charge state.
A bare SSD would show ion enhancements to 1 MeV, often would assume all is $H^+$, actual $H^+$ spectral index is very different!

Composition informs us that high E ions are He and O, if one assumed $q=1$, would require mass dependent gyromotion to drive greater energization of He and O

Inference of charge-state shows flux and enhancements are best ordered by $E/q$, matching previous results w/ charge-state [e.g. Möbius 1987] and indicative E-field driven energization, which is largely mass independent.
Substorm (\(\Delta E \approx 500\) nT) flows observed by MMS during w/ energetic ion enhancements

Ion fluxes well-correlated, corr table indicative of He being He\(^{2+}\), while Oxygen is separable – For \(E < 250\) keV O\(^+\), for \(E > 250\) keV O\(^{6+}\)

Again, He and O that reach higher energies than H\(^+\) (>300 keV), due to higher charge state.
Substorm ($AE \approx 750$ nT) flows observed by MMS during PS crossings w/ energetic ion enhancements

Ion fluxes are still well-correlated between different species for constant E/q. Helium is He$^{2+}$, ionospheric O$^+$ up to ~250 keV, solar wind O$^{6+}$ up to an MeV!
Example 4, ~8 $R_E$
Non-adiabatic Oxygen Energization

HPCA observes no O$^{2+}$ < 80 keV (40 keV/q)
Most likely, just O$^+$

Possible source of this extra O$^+$ energization is “pick-up” energization from induced E-field, e.g. Delcourt et al. (2002) JASTP.

Average kinetic energy gain:

$$E_{kin,avg} = 2 \times \frac{1}{2} m v^2_{E \times B}$$

For a flow ~550 km/sec, leads to ~50 keV difference between H$^+$ and O$^+$

Previous cases had clear ridges of corr along integer q values for He and O.
Highest corr of lower energy Oxygen (130-300 keV) is at energies between a factor of 1-2 of H$^+$ energies - constant offset in energies of ~50 keV
Is this a mix of O$^+$ and O$^{2+}$? Probably not! Likely only O$^+$
Summary

• Here we have shown 4 cases where we can use the correlation of flux between different energy channels of different species to deduce the charge state of highly suprathermal heavy ions in the magnetotail during substorm injections. These are representative of more the 50 cases we have identified with MMS-EIS data between 6-25 $R_E$

• At highly suprathermal energies ($E \gtrsim 200–300$ keV) heavy ions (helium and oxygen) dominate proton flux

• Correlation analysis shows that these highly suprathermal energies are multiple charge-state solar wind ions, which are well ordered with H+ for constant E/q

• Thus, mass-dependent non-adiabatic acceleration is not necessary to explain the very highly energetic tails of these species

• Only shown for 1 case here, but ratio of pre- to post- enhancement fluxes are well-ordered by $E/q$ for examples 1-3

• Evidence of cases with possible non-adiabatic “pick-up” energization, gives O+ an extra $\sim 50$ keV, but highest energy oxygen ($>300$) still primarily O$^{6+}$

• If you only take away one thing! Please don’t assume that “all-ion” measurements at highly suprathermal energies are H$^+$ or even singly charged, the spectral indices and energization you try to match in simulations won’t be right!
Multiple ways to get E/q ordering:

Ukhorskiy et al. [2018] test particle+MHD – as ions are trapped in magnetic islands, energization due to steep magnetic field gradients. Still found E/q dependence, while energization could be non-adiabatic.

Mitchell et al. [2018] purely adiabatic acceleration within flow channel.

Catapano et al. (2017) - test particle simulation of ions under stochastic e-m perturbations in the current sheet, ion energization was proportional to charge state and only weakly dependent on ion mass ($\propto m^{1/5}$).