Radial dependence of near-Earth space plasmas (5 to 26 \(R_E\))

Student & Presenter: Marissa Hedlund
PI: Lynn Kistler
Co-I: Chris Mouikis

Space Science Center, University of New Hampshire: Durham, NH, 03823

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Dynamics of magnetized spheres
  - Micro to macro scale
  - Trapped particle motion
    - Single particle motion
    - Field-aligned motion

Magnetospheres and ionospheres
  - The sun, Earth, and other bodies within our solar system
  - Magnetosphere-ionosphere coupling
    - The aurora and its relation to oxygen

Oxygen escaping Earth’s atmosphere into its magnetosphere
  - Ion transport mechanisms (this is what I study)
  - Satellites in the ionosphere and near-Earth space
    - Van Allen Probes (RBSP)
    - “Space weather” implications
Micro to macro sized magnetized spheres
Single particle motion

**Example:** In uniform magnetic field and absence of electric field, a charged particle moves in a circle. Assume that $\mathbf{B}$ is along $z$ axis and write $x$ and $y$ velocity terms $(v_x, v_y)$

\[
\mathbf{F}_L = q[\mathbf{E} + (\mathbf{v} \times \mathbf{B})]
\]

Assumptions: $(B = B_z)$

\[
\begin{align*}
    m\dot{v}_x &= qv_y B \\
    m\dot{v}_y &= -qv_x B
\end{align*}
\]

Momentum change:

\[
    m\frac{\mathbf{v}}{dt} = q[\mathbf{E} + (\mathbf{v} \times \mathbf{B})] + \mathbf{F}_g
\]

Angular frequency:

\[
    \omega = \frac{|q|B}{m}
\]

This could be also generalized to:

\[
\begin{align*}
    \dot{x}_j &= -(qB/m)^2 x_j = -\omega^2 x_j \\
    \dot{y}_j &= -(qB/m)^2 y_j = -\omega^2 y_j
\end{align*}
\]

- Charged particle motion in magnetic fields
- Ideal MHD
  - Ignores relativistic effects
**Trapped particle motion**

- **Gyromotion**: charged particles gyrate around center with circular motion perpendicular to the magnetic field ($\mathbf{B}$)
  - Parallel velocity is constant ($v_\parallel$)

- **Pitch angle**: the angular trajectory a charged particle is deflected at along $\mathbf{B}$ ($\alpha$)
  - 0°/180°: particle motion is field-aligned with $\mathbf{B}$
  - 90°: particle motion is a corkscrew along $\mathbf{B}$
  - For my studies:
    - **Parallel flow**: $0^\circ < \alpha < 30^\circ$ → field-aligned
    - **Perpendicular flow**: $80^\circ < \alpha < 100^\circ$ → gyromotion
    - **Antiparallel flow**: $150^\circ < \alpha < 180^\circ$ → field-aligned

\[
\tan \alpha = \frac{v_\perp}{v_\parallel}
\]

\[
\omega = \frac{|q|B}{m}
\]

\[
r_c = \frac{v_\perp}{\omega} = \frac{mv_\perp}{|q|B}
\]
Formation of Mars’ ionosphere:

Formation of Titan’s ionosphere:

Formation of Ganymede’s ionosphere:
Earth’s ionosphere

Ionospheric outflow
Magnetospheres

Formation of Earth’s magnetosphere:

Outer planets’ magnetospheres:
Heliosphere

Termination Shock

Bow Wave

Heliopause

Sun
Jovian magnetosphere
Magnetosphere-Ionosphere Coupling

Formation of field-aligned currents in near-Earth space:

Regions of Earth’s magnetosphere:
Occur in high-latitude region called auroral zone

Northern lights: aurora borealis

Southern lights: aurora australis

Optical emissions are caused when the solar wind is deflected towards Earth's magnetic poles and down field-lines to ionospheric altitudes (~80 to 640 km) where it then collides and ionizes atmospheric particles.

Higher solar activity $\rightarrow$ more high energy collisions $\rightarrow$ more lights

Formation of Aurorae
Magnetic dipolarization substorms

1. Magnetic reconnection

2. Magnetic field dipolarization

Just after substorm onset

Aurora

Plasmoid
Saturn’s Aurora

$H_3^+$ Faint X-rays

Hubble Space Telescope
Ion transport mechanisms

- Ionospheric $\mathrm{O}^+$ outflow enters the magnetosphere from either the dayside cusp or nightside auroral regions of very near-Earth space.

- $\mathrm{O}^+$ sourced from the nightside aurora has direct access to the plasma sheet and exhibits characteristic temporal energy dispersions.
  - Often injected into plasma sheet following magnetic dipolarizations.
Van Allen Probes (RBSP-A & RBSP-B)

- The 2 spacecraft were used to study the Van Allen radiation belts that encompass our planet
  - Ran out of fuel - will deorbit in 2034
  - No one expected them to last longer than 2 years because of the horribly violent environment they lived in

- NASA Goddard, Solar Dynamics Observatory (SDO), and The Johns Hopkins University Applied Physics Lab (APL) operate RBSP instruments
  - Often injected into plasma sheet following magnetic dipolarizations

Van Allen Probe B was shut-off 07/19/2019 and Van Allen Probe A was deactivated 10/18/2019 after operating for 7 years
Magnetosphere Multiscale Mission (MMS)

- MMS consists of 4 identical spacecraft
  - Studies how the Earth and Sun’s magnetic fields connect and disconnect
    - Magnetic reconnection events transfer massive amounts of energy and momentum
  - First mission to allow for small-scale, 3D structure of extremely dynamic systems (*microphysics*)
    - Renown for high spatial and temporal resolution instruments

- Spacecraft were launched 03/13/2015 and are estimated to remain operational until 2040
  - 3 phase mission to study *space weather*
Statistical study of MMS & RBSP


- For each data set:
  1. Identify $O^+$ dispersions (characteristic of nightside auroral source)
  2. Record maximum and minimum energies of dispersion
  3. Record flow direction (uni or bi-directional by pitch angle $\alpha$)
  4. Note if there was a dispersionless ion injection observed by LANL geosynchronous satellites
  5. Identify if injection followed dipolarization by checking for increase in $B_z$

- Sort through data sets for highest quality events (“Greatest Hits”)

**Phase 1b & 2**

**RBSP**

- 05/27/2016 to 04/30/2017
  - Apogee 6 $R_E$

**MMS 2016**

- 03/01/2016 to 09/25/2016
  - Apogee 13 $R_E$

**MMS 2017**

- 04/01/2017 to 10/26/2017
  - Apogee 26 $R_E$
Sample MMS Event

Dipolarizations

Ion injections

Instrument off

08-12-2016
Sample RBSP Event

Dipolarization

Ion injections
**Preliminary Results**

**Flow Direction of O⁺ Dispersions**

- Northern hemisphere
- Southern hemisphere

**Location of O⁺ Dispersions**

- Dipole L
- Dawn
- Noon
- Midnight
- Dusk

- MLT
Preliminary Results

Min E of O⁺ vs. Radial Distance

Max E of O⁺ vs. Radial Distance
Preliminary Results

<table>
<thead>
<tr>
<th>Data set</th>
<th>Total no. events</th>
<th>“Greatest Hits”</th>
<th>% with LANL</th>
<th>% with dipolarizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBSP</td>
<td>181</td>
<td>N/A</td>
<td>49.73% (total)</td>
<td>52.05% (total)</td>
</tr>
<tr>
<td>MMS 2016</td>
<td>261</td>
<td>80</td>
<td>31.25%</td>
<td>81.25%</td>
</tr>
<tr>
<td>MMS 2017</td>
<td>57</td>
<td>14</td>
<td>50%</td>
<td>64.29%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data set</th>
<th>$R_E$</th>
<th>Dipole L</th>
<th>Max E (keV)</th>
<th>Min E (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBSP</td>
<td>5.4</td>
<td>5.921</td>
<td>1.22</td>
<td>9.02</td>
</tr>
<tr>
<td>MMS 2016</td>
<td>9.9</td>
<td>11.38</td>
<td>15.0</td>
<td>127</td>
</tr>
<tr>
<td>MMS 2017</td>
<td>14.0</td>
<td>14.57</td>
<td>16.1</td>
<td>129</td>
</tr>
</tbody>
</table>
Conclusions from initial statistics:

- The number of dispersed O⁺ injections into near-Earth plasma sheet decrease with radial distance
  - Most events are occurring at <15Rₑ

- Locationally, we see a dusk-ward skewing of O⁺ energy dispersions

- The minimum/maximum energy of O⁺ dispersions agree with a model of a nightside aurora source
  - Model considers convection combined with parallel motion
GJ 1151

Illustration: Olena Shmahalo
Personnel & Acknowledgements

• Marissa is an analytical chemist by training
  • Started studying space physics in 2018 as a Boulder Solar Alliance REU Intern at HAO (NCAR)
• NASA: Living With a Star (LWS) Focus Science Team (FST) #3- Ion Transport
  • FST #3: Magnetosphere-Ionosphere Processes Responsible for Rapid Geomagnetic Changes

Yours truly

Chris Mouikis
Kevin Pham
Lynn Kistler
Bill Lotko
Thank you for listening!
Any questions?
Extras
Perceived Impact

• Determine solar wind parameters, magnetospheric conditions, and ionospheric properties that affect the rate of change of the geomagnetic field in the coupled solar wind – magnetosphere – ionosphere system

• Establish a predictive capability for geomagnetically induced current (GIC) events
  o Can disrupt telecommunications and electrical grid systems
  o Hazardous for humans aboard ISS
Sample RBSP O\textsuperscript{+} Dispersion

Dipolarization

Ion injections

08-02-2016
Sample MMS Multi-Dispersed Event

No dipolarization

No ion injection at times of dispersions at geosynchronous
Dipolarizations

No ion injection
Sample MMS O$^+$ Dispersion

H$^+$

O$^+$

Dipolarizations

Ion injections

Instrument off

08-12-2016