Plasma measurements in Jupiter’s magnetosphere

By: Rob Ebert
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Workshop on Jupiter’s Aurora, Anticipating Juno’s Arrival – March 8th, 2016
Previous Missions to Jupiter

Fig. 4 from Bagenal et al. 2014, SSRv
Summary of Plasma Observations

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Instrument</th>
<th>Timeframe</th>
<th>Energy Range</th>
<th>Regions Explored at Jupiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer 10</td>
<td>Plasma Analyzer (PA)</td>
<td>DOY 330 – 356, 1973</td>
<td>0.1 – 18 keV (protons) 0.001 – 0.5 keV (electrons)</td>
<td>foreshock, dawn magnetosheath, inner/outer magnetosphere</td>
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<tr>
<td>Pioneer 11</td>
<td>Plasma Analyzer (PA)</td>
<td>DOY 330 – 344, 1974</td>
<td>0.1 – 18 keV (protons) 0.001 – 0.5 keV (electrons)</td>
<td>foreshock, dawn magnetosheath, outer, inner and mid-latitude magnetosphere</td>
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<tr>
<td>Voyager 1</td>
<td>Plasma Science (PLS)</td>
<td>DOY 59 – 81, 1979</td>
<td>0.01 – 6 keV/q (ions) 0.004 – 6 keV (electrons)</td>
<td>foreshock, dawn magnetosheath, equatorial inner &amp; outer, inner and mid-latitude magnetosphere</td>
</tr>
<tr>
<td>Voyager 2</td>
<td>Plasma Science (PLS)</td>
<td>DOY 183 – 225, 1979</td>
<td>0.01 – 6 keV/q (ions) 0.004 – 6 keV (electrons)</td>
<td>foreshock, dawn magnetosheath, equatorial inner &amp; outer, inner and mid-latitude magnetosphere</td>
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<tr>
<td>Ulysses</td>
<td>Solar Wind Observations Over the Poles of the Sun (SWOOPS)</td>
<td>DOY 33 – 47, 1992</td>
<td>0.255 – 34.4 keV/q (ions) ~0.001 – 0.814 keV (electrons)</td>
<td>foreshock, dawn magnetosheath, equatorial inner &amp; outer, inner and mid-latitude magnetosphere</td>
</tr>
<tr>
<td>Galileo</td>
<td>Plasma Particle Investigation (PLS)</td>
<td>DOY 341, 1995 – DOY 264, 2003</td>
<td>0.9 – 52 keV/q (ions) 0.9 – 52 keV (electrons)</td>
<td>equatorial inner &amp; outer magnetosphere, satellite flybys</td>
</tr>
<tr>
<td>Cassini</td>
<td>Cassini Plasma Spectrometers (CAPS)</td>
<td>October 2000 – April 2001</td>
<td>~0.001 – 50 keV (ions) 0.6 – 28 keV (electrons)</td>
<td>dusk bow shock, dawn magnetosheath, and boundary layer</td>
</tr>
<tr>
<td>New Horizons</td>
<td>Solar Wind Around Pluto (SWAP)</td>
<td>DOY 56 – 173, 2007</td>
<td>0.02 – 7.5 keV/q (ions)</td>
<td>dusk magnetosphere, distant magnetotail, boundary layer and magnetosheath</td>
</tr>
<tr>
<td>Juno</td>
<td>Jovian Auroral Distributions Experiment (JADE)</td>
<td>JOI 7/4/2016</td>
<td>0.01 – 50 keV/q (ions) 0.1 – 100 keV (electrons)</td>
<td></td>
</tr>
</tbody>
</table>
Juno Approach
Upstream Solar Wind


- Dynamic pressure distributions of ICMEs and CIRs appear bimodal.
  - Less apparent when considering all SW types.
- SW obs. upstream of Jupiter are needed to infer correlations between SW and remotely observed auroral emissions.
- Plenty of discussion regarding role of solar wind in driving variations in auroral emission features.

- Simultaneous observations of upstream solar wind/IMF and remotely sensed auroral emissions are needed to accurately identify correlative relationships.

- Understanding gained from these studies will help guide interpretation of the auroral observations when Juno is inside the magnetosphere.
Magnetospheric Boundaries

- Plasma observations provide a definitive signature of magnetospheric boundaries.
- Location of boundaries constrain the shape and extent of the magnetosphere.
- Aurora emissions may vary with boundary motion.
- There are several theoretical models describing SW-magnetospheric interactions at Jupiter but few observational constraints.

- Additional observations of the plasma flow, density, temperature and composition inside the magnetopause and in the outer magnetosphere are needed.
- Understanding how the SW couples to the magnetosphere has important implications for global magnetospheric dynamics.
Juno will explore Jupiter’s:
- Auroral regions
- Polar magnetosphere
- Plasma sheet
- Outer magnetosphere/cushion region
- Little to no \textit{in situ} plasma observations in many of these regions.
The Big Picture

The magnetosphere of Jupiter extends 63–92 Jovian radii in the direction towards the Sun, with a tail that stretches beyond the orbit of Saturn. Intense auroral emissions are signatures of the coupling between the planet and the magnetospheric plasmas. The Juno spacecraft will fly through the regions where the aurora-generating particles are excited.

Jupiter's strong magnetic field makes the magnetosphere of Jupiter the largest object within the heliosphere (Fig. 1), stretching in the direction towards the Sun for typical distances of 63–92 \( R_J \) (the radius of Jupiter, \( R_J = 714,920 \) km at the 1 bar level, see the Appendix). Over a ton/second of Io's SO2 atmosphere escapes the satellite. The escaping neutrals are dissociated, ionized and trapped by the magnetic field. The resulting dense (\( \sim 2000 \) particles/cm\(^3\)) torus of plasma, roughly co-rotates with Jupiter's \( \sim 10 \) hour spin period. The ions of sulfur and oxygen (Ti \( \sim 100 \) eV) are excited by the \( \sim 5 \) eV thermal electrons and radiate \( \sim 1 \) terawatts of UV emission. Rather than cooling on expansion, the iogenic plasma is heated (by an as-yet-unknown process) to temperatures of \( \sim 10 \) s keV as it is transported radially outwards (via flux tube interchange motions) on timescales of weeks. Coupling of the magnetospheric plasma to Jupiter's rotating atmosphere dominates the dynamics of the magnetosphere, the ensuing strong centrifugal forces producing an extended, equatorially-confined plasmadisk. Associated with the electrical currents that couple the magnetospheric and ionospheric plasmas are intense auroral emissions that span the spectrum from X-rays to radio. The hot plasma in Jupiter's plasmadisk inflates the magnetosphere, making it larger and more compressible than a magnetic dipole alone. While the vast
Plasma Sheet

Jupiter

Half lost as fast neutrals
-> extended neutral cloud

Half transported out to plasma disk

Delamere & Bagenal 2003

- Ions are picked up by Jupiter’s magnetic field, spun up to the planet’s rotation rate and transported radially outward.
Plasma Sheet

Bagenal et al. 1981, reprocessed data shown here by Bodisch et al. 2015; Dougherty et al. 2015

- Plasma mass density dominated by heavy ions.

- Data shown here reprocessed to include estimates for O$^+/S^{++}$ based on Cassini UVS observations + physical chemistry model (e.g. Delamere, Steffl, and Bagenal, 2005).
Plasma Sheet

- Juno can provide new insight into the vertical and radial profiles of the plasma sheet, including measuring the conditions within days of the perijove passes through the auroral region.
- Plasma co-rotation starts to break down at ~17 - 20 R_J (e.g. McNutt et al. 1981).
- Coupling currents and corresponding aurora are stronger in region where plasma slips behind corotation (e.g. Hill 1979).
Frank and Paterson, 2002

Electron pitch angle and energy distributions provide information about these currents.
Polar Magnetosphere

Little to no *in situ* plasma measurements, many fundamental questions:

- What is the high latitude structure of the magnetosphere? Is it fundamentally similar or different than Earth?
- Where and how are the particles that excite the aurora generated?
- How do the currents close between the plasma disk and the aurora region?
- What causes the transient polar aurora?
- How open is the magnetosphere to the IMF?
- What is the size and the variability of Jupiter’s polar cap?
- How is the main aurora related to magnetospheric dynamics and/or changes in the solar wind?
- Is there significant outflow from Jupiter’s ionosphere? How much does it contribute to Jupiter’s plasma environment?
Electron and ion observations are needed to help discover the structure and location of the auroral acceleration regions at Jupiter.

What will this sketch look like for Jupiter?
Precipitating Electrons

- Remote sensing observations used to estimate mean energy and energy flux of precipitating electrons; suggest spatial variability.
- Observations from Juno will provide ground truth.
Conclusions

- Plasma measurements from 8 previous missions have revealed a lot about the structure of and dynamics within Jupiter’s magnetosphere.

- There are still many open questions.

- Juno’s orbit provides an opportunity to make observations in several regions of the magnetosphere that are either under-sampled or completely unexplored.

- Key objective is to determine the structure of the region that accelerates the particles that produce the aurora.

- Many other high impact science opportunities during mission.