Saturn’s magnetosphere after the Cassini
~ Works related to RPWS/LP ~

M. W. Morooka\(^{(1)}\), J.-E. Wahlund\(^{(2)}\),
M. K. G. Holmberg\(^{(2)}\), O. Shebanis\(^{(2)}\), and E. Odanaka\(^{(1)}\)
\(^{(1)}\) PPARC, Tohoku University, \(^{(2)}\) IRF Uppsala
Langmuir Probe (LP)

- TiN coated sensor (5 cm)
- Cold Plasma
  - Number density \((N_e, N_i)\)
  - Temperature \((T_e)\)
  - Ion drift speed \((V_{di})\)
  - Spacecraft (dust) potential \((U_{SC})\)

- Electron density in tenuous plasma \((N_e)\)
Radio and Plasma Wave Science/Langmuir Probe
Cassini RPWS/LP

Langmuir Probe (LP)
- TiN coated sensor (5 cm)
- Cold Plasma
  - Number density ($N_e, N_i$)
  - Temperature ($T_e$)
  - Ion drift speed ($V_{di}$)
  - Spacecraft (dust) potential ($U_{SC}$)
- Electron density in tenuous plasma ($N_e$)

LP Science
- Titan atmosphere
- Ring ionosphere and icy moons
- Outer magnetosphere dynamics
Radio and Plasma Wave Science/Langmuir Probe
Cassini RPWS/LP

Outer magnetosphere dynamics

Ring ionosphere and icy moons

Titan atmosphere

Magnetosphere similar to the Earth
Different in:
Strong control of co-rotation
Contains E ring and icy moons as plasma source
Periodic structure of the magnetosphere

Electron densities by LP in the outer magnetosphere
Periodic structure of the magnetosphere 
(In-situ)

- Magnetic field data from Pioneer 11, Voyager 1 and 2, ‘cam shaft’ model by Espinosa et al., [2000]
- Periodic electrons/ions (few tens to hundred keV) modelation by Voyager 1 and 2 [Carbary and Krimigis, 1982], and Cassini [Krupp et al., 2005]
- Magnetopause oscillation. [Clarke et al., 2006]
- The electron densities near the Enceladus orbit [Gurnett et al., 2007]
- Low energy (few hundreds eV) electron [Arridge et al., 2008]
- Periodicity similar to SKR of Spoke [Porco and Danielson 1982]

The planetary spin modulation was mystery since magnetic dipole axis of Saturn is almost parallel to the spin axis.
Periodic structure of the magnetosphere (In-situ)

Small magnetic dipole tilt angle can make plasma sheet flapping. The sun direction was from the southern hemisphere during the first four years.

Arridge et al., [2008]
Test 1: longitudinal asymmetry

Simulated data and observed data perfectly match. Southern/Northern periodicity are in phase.
Test 2: CS flapping in spin period

Peak matches in the south but out of phase in the north. North/South periodicity becomes out of phase.
Periodic structure of magnetosphere 
\textit{(In-situ)}

Flapping plasma sheet AND longitudinal asymmetry  
[Khurana et al., 2009]
Periodic modulation of the magnetosphere

*Remote sensing*

ENA’s integrated intensity shows periodicity.

Paranicas et al., [2005]
Periodic modulation of the magnetosphere (Remote sensing)

Periodic occurrence of plasma energization and its association to SKR and UV aurora. Michel et al., [2009]
Periodic modulation of the magnetosphere (Model)

Electron density modulation around Enceladus orbit

Gurnett et al., [2007]

Co-rotating convention system makes plasma outflow from one longitude.
Periodic modulation of the magnetosphere (Model)

Localized vortical flow in one hemisphere creates the periodicities in the magnetosphere and on another ionosphere.

Jia et al., [2012]
Spectrograms of SKR signals show two periodicities: one from north (left hand polarization) and another from south. Lamy et al., [2008]

There are no other observations that show dual periodicity so far.

Magnetic field also shows different periodic FAC system in north and south.

Radio and Plasma Wave Science/Langmuir Probe

Cassini RPWS/LP

Ring ionosphere and icy moons

Outer magnetosphere dynamics

Titan atmosphere
Titan atmosphere and its interaction with Saturn’s magnetosphere

**Space environment**
- Ionizing radiation (Solar EUV/X, Energetic particles)
  - Triggers upper atmospheric chemistry
    - in a \( N_2 - CH_4 \) atmosphere
    - Produce complex organic molecules (via \( N_2^+, N^+ \))
    - Leads to formation of organic aerosol (“haze”)
    - Deposition on surface (+H\(_2\)O \( \Rightarrow \) Hydrolysis)

**Ex: Titan, Early Earth?**
Titan atmosphere and its interaction with Saturn’s magnetosphere

Ionization sources depends on orbit position.

Ionosphere influence
- Solar EUV/X
- Magnetospheric particle impacts
- Magnetospheric electrodynamics
- Dayside to nightside transport
- ...
Titan cold plasma outflow

- Titan wake divided into two structures:
  - Heavy ions on Saturn side
  - Light ions on ant-Saturn side

- Plume of escaping Titan ionosphere assoc. with magnetic field perturbation.

- Modolo et al., [2007]
- Edberg et al., [2011]

Review by Wahlund et al., in print
Titan meats the solar wind shock region

- Titan’s flow-induced magnetosphere was populated by “fossil” fields originating from Saturn.
- Reconnection may have been involved in the replacement of the fossil fields by the interplanetary magnetic field.

Bertucci et al., [2008]
Titan

- Titan’s ionosphere is a substantial source for aerosol formation & other complex organic chemistry
  - Ionization sources and formation of ionosphere (mostly HCNH\(^+\), C\(_2\)H\(_5\)\(^+\))
    - [Wahlund et al., 2005; Cravens et al., 2005; Ägren et al., 2009]
  - Presence of heavy (up to 40000 amu) negative organic ions
    - [Coates et al., 2007; 2010]
  - Presence of heavy (up to at least 350 amu) positive organic ions
    - [Waite et al., 2007]
  - Heavy positive ions (>100 amu) recombine and deposit 0.1-1 Mton/yr
    - [Wahlund et al., 2009; Crary et al., 2009; Sittler et al., 2009]
  - Large amount (dominant part) of heavy negative ions in lower ionosphere
    - [Ägren et al., 2012]
  - Can explain Aerosol growth
    - [Lavvas et al., accepted, 2012; Shebanits et al., in preparation 2013]
Detection of Complex Chemistry

Tholin formation? Waite et al., [2007]
Compare with laboratory measurements. Vuitton et al., [2007, 2008]
Detection of Negative Ions $>10000$ amu/q

- [Coates et al., 2007; 2010]
- Dissociative e$^-$-attachment?
  - Darkness $\Rightarrow$ No photo-detachment
- Up to $200$ cm$^{-3}$
  - Large fraction of $N_e$
- Charge
  - $U \approx k_B T_e \sim -0.25 \text{ V}$
  - Ca 5e/ion
  - 50000 amu
  - 10-30 nm!
- Initial stages for aerosol (tholin) formation?

- Catalytic polymerization
  - CN$^-$, NH$_2^-$, (O$^-$)
  - NCN$^-$, HNCN$^-$, C$_3$H$^-$
  - C$_5$H$_5^-$, C$_6$H$^-$, C$_6$H$_5^-$
  - Polyenes, Nitriles
  - PAH
  - Cyano-aromatics
LP observations of Heavy organic ions in Titan’s Lower Ionosphere

More heavy negative ions detected on the nightside.

Shebanits et al, submitted
Radio and Plasma Wave Science/Langmuir Probe
Cassini RPWS/LP

Outer magnetosphere dynamics
Ring ionosphere and icy moons
Titan atmosphere
Enceladus
Enceladus plume detected by MAG

• Bx shows the expected Alfvén wing of the southern plume.
• By are rather difficult to interpret.

Dougherty et al. (2006)

Magnetic perturbation even in the north!
Dusty Plasma evidence at the Enceladus

The electron density is very small (1% of ions!) because they are sucked up by the dust.

Morooka et al., [2011]
Electron dropout coincide with the RPWS dust impact

Farrell et al. [2009, 2010]

Positive and negative grain detection as high energy particles

RPWS & CAPS

Electron dropout
dust hit impact

corotating ion slowing down

CAPS Corotating Ions (A7)

20 kHz dust
Charged dust and plasma collective effect

NO $N_i$ WAKE

Plasma in the same speed as the moon (no co-rotation)

$V_i < V_{\text{co-rotation}}$
Dusty Plasma?

Plasma = electrons + ions
Dusty Plasma = electrons + ions + small body
  ↓
absorbs electron/ion and get charged

- Dust are a significant element of the Universe.
- Gravity force is usually focused for the dust dynamics.
  \[ m_e \sim 9 \cdot 10^{-31} \text{ kg} \quad m_{i \text{(water)}} \sim 10^{-26} \text{ kg} \]
  \[ m_d \sim 10^{-24} \text{ kg (1 nm size)} \quad 10^{-15} \text{ kg (1 \( \mu \)m size)} \]
- Dust are affected by the electro-magnetic force when they get charged and interact with plasma.
  \[ q_d \sim \text{few (1 nm size)} \quad 10^3 \text{ charge (\( \mu \)m)} \]
  \[ (M/Q)_d = 10^2 \sim 10^8 (M/Q)_{ion} \quad (m_i/m_e) \sim 10^4 \]
This results very low gyro-frequencies are expected:
  \[ \Omega_d \sim 10^{-2} \sim 10^{-6} \text{ [Hz]} \text{ at the Enceladus (B=328[nT])} \]
  \[ r_{gd} \text{ to be } 20 \sim 10^5 \text{ [km]} \quad (r_{gi} \text{ to be } 20 \text{ [km]}) \]
Electrons are attached to the dust near the E ring.

Cassini RPWS LP  Start Date: 2005.07.14

Wahlund et al., [2009]
Electron density dip is found in ~50 % of all the orbit around the Enceladus.

Density dip centered at $Z = \pm 0.02 \, \text{Rs}$

Density dip width is about $\pm 0.09 \, \text{Rs}$. ... ~ E ring width.

The north/south asymmetry of electron density.
Dust potential in the Saturn’s magnetosphere
Juhász and Horányi, [2002 JGR]

Ion outflow starts when $U_d$ becomes positive?

$V_i$ in the equatorial plane ($R_Z \pm 0.5$) [Holmberg et al., 2012]
Cassini orbits around Saturn

Equinox season

Solstice season