Les ceintures de radiation de la Terre, Jupiter et Saturne: similitudes et différences

A. Sicard-Piet, S. Bourdarie, D. Boscher, L. Lorenzato, V. Maget, D. Lazaro, S. Rochel
ONERA/DESP, Toulouse, France
**Introduction**

**Planetary magnetospheres:**

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mercury</th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obliquity to orbit (°)</td>
<td>0.01</td>
<td>23.5</td>
<td>3.1</td>
<td>26.7</td>
<td>97.8</td>
<td>28.3</td>
</tr>
<tr>
<td>Magnetic moment (G.Rp³)</td>
<td>0.0033</td>
<td>0.301*</td>
<td>4.28</td>
<td>0.21</td>
<td>0.228</td>
<td>0.142</td>
</tr>
<tr>
<td>Dipole tilt to rotation axis (°)</td>
<td>169</td>
<td>169.5*</td>
<td>9.6</td>
<td>&lt; 1</td>
<td>58.6</td>
<td>46.9</td>
</tr>
<tr>
<td>Rp (km)</td>
<td>2439</td>
<td>6371</td>
<td>71398</td>
<td>60330</td>
<td>25600</td>
<td>24765</td>
</tr>
</tbody>
</table>

**Equation:**

\[
\vec{F} = q\left(\vec{E} + \vec{v} \wedge \vec{B}\right)
\]
Radiation belts composition and structure

- **Electrons**
  - Spectrum: 10 keV-10 MeV
  - Location: 1-10 Re
  - Origin:

- **Protons**
  - Spectrum: 10 keV-300 MeV
  - Location: 1-10 Re
  - Origin: + CRAND

- **Heavy ions**
  - Helium:
  - Oxygen ?:

- **Electrons**
  - Spectrum: 100 keV-300 MeV
  - Location: 1-20 Rj
  - Origin:

- **Protons**
  - Spectrum: 100 keV-1 GeV
  - Location: 1-20 Rj
  - Origin: + CRAND

- **Heavy ions**
  - Helium: + Io
  - Oxygen: + Io
  - Sulphur: Io

- **Electrons**
  - Spectrum: 10 keV-10 MeV
  - Location: 1-10 Rs
  - Origin:

- **Protons**
  - Spectrum: 100 keV-100 MeV
  - Location: 1-10 Rs
  - Origin: + CRAND

- **Heavy ions**
  - Helium: + Enceladus
  - Oxygen: + Enceladus
Radiation belts composition and structure

Earth

Electron

Proton

Jupiter

Electron

Proton

Ring of dust
Metis and Adrastea
Amalthea
Thebe
Io
Europa
Ganymede
Callisto
Main physical processes in the radiation belts

Interaction of energetic particles with:

- Atmosphere
- Rings
- Moons
- Plasmasphere
- or Neutral cloud
- or Io torus
- Waves

Radial diffusion

Earth

Saturn

Jupiter
Radiation belts composition and structure

Electrons

Earth

AE8 min  Electrons > 500 keV

Jupiter

Salammbô Electron > 21 MeV

Saturn

Salammbô Electron 380 keV

Radial diffusion from the tail

Atmospheric losses

Wave particle interaction

Rings and moons losses
Radiation belts composition and structure

**Protons**

*Earth*

AP8 min  Electrons > 10 MeV

(cm² s⁻¹)

*Jupiter*

Salammbô Proton > 30 MeV

(MeV⁻¹ cm² s⁻¹ sr⁻¹)

*Rings and moons losses*

Atmospheric losses

Radial diffusion from the tail

CRAND

Saturn

Salammbô Proton not developed yet

(Rings and moons losses)
Radiation belts composition and structure

**Protons**

**Electrons**

SAC-C/ICARE Proton 9.65-11.35 MeV

SAC-C/ICARE Electron 450-510 keV
Radiation belts dynamics

Atmospheric heating

Protons events

Magnetic storms

Cosmic rays

Particles injection

Neutron decay

Source of protons

Crossings particles

Particules losses
Radiation belts dynamics

**Short time scale dynamics**

*Electrons*

- Magnetic storm March 1991
- Filling of the slot region
- Enrichment of the inner belt

*Protons*

- Solar flares
- Temporary second belt
Radiation belts dynamics

Injection events seen by Galileo/EPD on November 06, 1996 between Ganymede and Europa

Plasma injection events seen by CASSINI/CAPS/ELS on October 30, 2005 at L=7

Figure 1. Logarithm of electron differential energy flux (log$_{10}$ D$E$F) plotted as a function of time and energy around 0737 UT on day 303 of 2005.

Radiation belts dynamics

Long time scale dynamics

Year

Flux (keV⁻¹ cm⁻² s⁻¹ sr⁻¹)

1.0 × 10⁰
1.0 × 10¹
1.0 × 10²
1.0 × 10³
1.0 × 10⁴
1.0 × 10⁵

1976
1981
1986
1991
1996
2001

50-75 keV
75-105 keV
105-150 keV
150-225 keV
225-315 keV
315-500 keV
500-750 keV
750-1100 keV
1100-1500 keV
Radiation belts dynamics

Long time scale dynamics

Radiation belts observations

Many different orbits and many observations of the Earth radiation belts

- GPS (20000 km - 55°)
- Geostationary (35500 - 0°)
- SPOT (800 km - 98°)
- CONSTELLATION (1400 km - 52°)

Graph showing radiation belt observations for different orbits:
- GEO
- HEO
- GTO
- MEO
- LEO
- PEO

Coverage and time/date plots for each orbit.
Radiation belts observations

Few observations: in-situ measurements by interplanetary missions and synchrotron measurements on the ground

- Pioneer 10 and 11
- Voyager 1 and 2
- Galileo Orbiter
- Galileo Probe
- Ulysses
Radiation belts observations

Even few observations: in-situ measurements by interplanetary missions

Comparaison with Salammbo

Pioneer 11
- $e^{-} : > 40$ keV

Cassini
- $e^{-} : 175-300$ keV
Specification models

AP8 >10 MeV

AE8 >1 MeV

Global models
- AE8/AP8 (NASA)
- AE9/AP9 (Aerospace)

Local models
- IGE-2006 at GEO (ONERA)
- MEO-V2 at MEO (ONERA)
- Slot model (ONERA)
- OPAL protons at LEO (ONERA)

JOSE Elec >10 MeV

JOSE Prot >1 MeV

Global models
- D&G 1983 (JPL)
- GIRE (JPL)
- JOSE (ONERA)

Global model
- SATRAD(JPL)
Perspectives

- Improvement of the understanding and modeling of the physical processes in the radiation belts
- Study of the link between solar wind parameters and radiation belts dynamics (space weather)
- Development of a global model for Earth radiation belts

- Comparison of synchrotron mapping derived from Salammbô results and LOFAR observations
- Study of the dynamics of the Jovian radiation belts (link with solar wind)

- Modeling of protons radiation belts
- Modeling of Uranus radiation belts