Plasma interactions at Titan and icy moons: evolving ionospheres

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Outline:

• Titan, Enceladus, Rhea, Dione
• Ionospheric escape at solar system objects
• Ganymede, Europa, Callisto
• Conclusions
Titan flyby, 16 April 2005

Waite et al., Science 2005

From INMS
Titan negative ions
- Unexpected!
- Ram direction
- Near closest approach

Confirmed in later low altitude encounters

Originally seen on TA in 2004…

Coates et al., GRL 2007
Titan’s atmosphere: a hydrocarbon chemical factory producing haze in Titan’s atmosphere and tholins for the surface

Unexpected heavy **negative ions**: Coates et al, 2007, 2009, 2010

Escape - Coates et al 2012

Heavy **neutrals and positive ions**: Waite et al, 2007, Crary et al. 2009
First chemical model including negative ions (low mass), c.f. ELS data at 1015 km (T40) (Vuitton et al., PSS 2009)

High mass population: chains, rings, higher? PAHs (Waite et al., 2007, Coates et al., 2007)? Fullerenes (Sittler et al., PS 2009) at high masses?

Production processes:
- Several considered and rates estimated
- Mainly dissociative electron attachment

Loss processes:
- Several considered and rates estimated
- Mainly associative detachment
- Some photodetachment
Evolution of Titan ionosphere composition with altitude

Maximum mass of negative ions at Titan increases with decreasing altitude

Adapted from Coates et al., PSS 2009

New work on formation of large ions, Lavvas et al., 2012
Enceladus plume

Magnetometer data indicates plasma source (Dougherty et al., 2006)

Flow deflection indicates rate ~100-300 kgs\(^{-1}\) (Tokar et al., 2006)
Unexpected discoveries from Cassini at Enceladus

Charged nanograinns
Jones et al., GRL, 2009

Negative ions in the plume
Coates et al., Icarus 2010, Faraday Discussions 2010
Number density evolving with distance in plume:
Indicates charging by ambient plasma particles (Hill et al., 2012)

Additional charged particle population: a ‘dusty plasma’?
(Morooka et al., 2011)
Enceladus’ auroral spot

Pryor, Rymer et al., Nature
21 April 2011
Rhea’s $O_2$ and $CO_2$ atmosphere – from INMS and CAPS
Science Express – 25 Nov 2010

In-situ neutral atmosphere measurements (INMS)

Negative and positive ions picked up from atmosphere pinpoint near-surface source (CAPS)
Dione’s oxygen exosphere

Tokar et al., Geophys Res Lett., Feb 2012

Icy Dione is within Saturn’s trapped radiation belts – oxygen forms and is recycled via the surface

Process occurs at Dione, Rhea and Saturn’s main rings, also at Ganymede, Europa and Callisto in Jupiter's - targets for ESA’s proposed JUICE (JUpiter ICy moons Explorer) mission for launch in 2022
Ionospheric plasma near unmagnetized objects

Ionospheric photoelectrons – from measured electron spectrum, found well away from the objects

Titan, Coates et al., 2007, Wellbrock et al., 2012

Also related ion escape

Mars, Coates et al., 2011

Venus, Coates et al., 2008
Cassini in Titan’s tail: CAPS observations of plasma escape

- Only 3 distant tail encounters so far
- T9, T75 ~10,000 km tailward from Titan, T63 ~5,000 km
- Escaping ionospheric plasma seen well away from Titan – key is ‘fingerprint’ from ionospheric photoelectrons
- Split tail seen all 3 – common feature
- Escaping ionospheric ions mass-separated to give escape rate, combine with electron density gives flux
- $2.5 \times 10^{24}$ ions s$^{-1}$ (average)
- $4.8 \times 10^{25}$ amu s$^{-1}$ (average)
- …or 7 metric tonnes per day lost from atmosphere – significant on solar system timescale – but ~1/4000 Enceladus rate
## Comets – gas production rates

<table>
<thead>
<tr>
<th>Object</th>
<th>Spacecraft</th>
<th>Production rate (s⁻¹)</th>
<th>Ratio (Halley=100)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giacobini-Zinner</td>
<td>ICE</td>
<td>4x10²⁸</td>
<td>5.8</td>
<td>Mendis et al, 96</td>
</tr>
<tr>
<td>Halley</td>
<td>Giotto, Vega, Suisei, Sakigake</td>
<td>6.9x10²⁹</td>
<td>100</td>
<td>Krankowsky et al, 86</td>
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<tr>
<td>Grigg-Skjellerup</td>
<td>Giotto (GEM)</td>
<td>7.5x10²⁷</td>
<td>1.1</td>
<td>Johnstone et al, 93</td>
</tr>
<tr>
<td>Borrelly</td>
<td>DS1</td>
<td>3.5x10²⁸</td>
<td>5.1</td>
<td>Young et al, 2004</td>
</tr>
<tr>
<td>Churyumov-Gerasimenko</td>
<td>Rosetta</td>
<td>3x10²⁴-5x10²⁷</td>
<td>4.3x10⁻⁴-0.7</td>
<td>Hansen et al., 07, Motschmann &amp; Kuehrt, 06</td>
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From Coates, AIP proceedings, 2010
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<th>$Q \left( \text{Halley}=100 \right)$</th>
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<tr>
<td>Mercury</td>
<td>Ground based</td>
<td>$10^{24}-10^{25}$</td>
<td>$1.5 \times 10^{-4}-1.5 \times 10^{-3}$</td>
<td>Potter et al., 02</td>
</tr>
<tr>
<td>Venus</td>
<td>VEx, PVO</td>
<td>$10^{24}-10^{25}$</td>
<td>$1.5 \times 10^{-4}-1.5 \times 10^{-3}$</td>
<td>Brace et al., 87, Barabash et al., 07a</td>
</tr>
<tr>
<td>Mars</td>
<td>MEx, Phobos</td>
<td>$10^{23}-10^{25}$</td>
<td>$1.5 \times 10^{-5}-1.5 \times 10^{-3}$</td>
<td>Barabash et al., 07b Lundin et al., 08, 89</td>
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## Moons – gas production rates

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<th>Q (s⁻¹)</th>
<th>Q (Halley=100)</th>
<th>Reference</th>
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<tr>
<td>Io</td>
<td>Galileo</td>
<td>3x10²⁸</td>
<td>4.3</td>
<td>Bagenal, 94</td>
</tr>
<tr>
<td>Europa</td>
<td>Galileo</td>
<td>2x10²⁷</td>
<td>0.29</td>
<td>Smyth &amp; Marconi, 06</td>
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<tr>
<td>Ganymede</td>
<td>Galileo</td>
<td>1.3x10²⁷</td>
<td>0.19</td>
<td>Marconi, 07</td>
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<tr>
<td>Titan</td>
<td>Cassini</td>
<td>4x10²⁴-10²⁵</td>
<td>1-1.5x10⁻³</td>
<td>Coates et al., 12, Wahlund et al., 05</td>
</tr>
<tr>
<td>Enceladus</td>
<td>Cassini</td>
<td>3x10²⁷ – 1-2x10²⁸</td>
<td>0.43 - 2.9</td>
<td>Tokar et al., 06</td>
</tr>
<tr>
<td>Enceladus L-shell</td>
<td>Cassini</td>
<td>3.8-7.6x10²⁶</td>
<td>0.06-0.12</td>
<td>Cowee et al., 09</td>
</tr>
<tr>
<td>Rhea</td>
<td>Cassini</td>
<td>2.45x10²⁴</td>
<td>3.6x10⁻⁴</td>
<td>Teolis et al., 10</td>
</tr>
<tr>
<td>Dione</td>
<td>Cassini</td>
<td>9.6x10²⁵</td>
<td>0.01</td>
<td>Tokar et al., 12</td>
</tr>
</tbody>
</table>

Log radius (km)

Log $Q$ (s$^{-1}$)

Planets
- Mars lo
- Venus lo
- Merc lo
- Titan
- Venus hi
- Merc hi
- Enc lo
- Enc hi
- Rhea

Moons
- Io
- Enc L-shell
- Europa
- Enc.
- Dione

Comets
- Borrelly
- Halley
- GS
- GZ
Magnetosphere Science with JUICE

GANYMEDE ENVIRONMENT  JUPITER MAGNETOSPHERE  EUROPA FLYBYS

Dipole magnetic field and mini-magnetosphere

Coupling to Jupiter’s magnetosphere

Ganymede

Year 2030 2031 2032 2033
Conclusions

- Titan atmosphere – evolution with altitude, and plasma escape causing evolution with time
- Enceladus – evolution with distance, plasma escape
- Rhea and Dione – weak atmospheres (cf. Saturn rings, Europa, Ganymede, Callisto…)
- Planets, comets, moons group in production rate v size
- Anticipate JUICE in-situ characterisation of Galilean satellites in 2030s