Electrons in the Plume of Enceladus and the Role of Grain Interactions

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Boulder DAP 2012 June 2012
Plume and Torus Electrons and Ions - some references

- Cravens et al. (2011) (torus electrons)
- Ozak et al. (2012) (plume electrons)
- Cravens et al. (2009) (plume ion composition)
- Pothapragada - poster here at DAP (plume ions and grains)
Grains in the Enceladus Plume (and E-ring) - some references

- Kempf et al. (2008)
- Hsu et al. (2011, 2012)
- Hill et al. (2012)
- Jones et al. (2009)
- Morooka et al. (2011)
- ........
Enceladus Plumes - a visible ISS image - sunlight scattering off ice grains (Porco)
Cassini-Enceladus Plume Encounter Geometry.

The E3 and E7 passes are the focus of this talk.
Enceladus: Cassini INMS Mass Spectra of the Atmosphere of Enceladus (E2) - Waite et al. 06

- H$_2$O $91 \pm 3\%$
- CO$_2$ $3.2 \pm 0.6\%$
- CO or N$_2$ $4 \pm 1\%$
- CH$_4$ $1.6 \pm 0.4\%$

Waite et al., 2007
\( n_e \approx 80 \text{ cm}^{-3} \) and \( V_{\text{cor-enc}} = 26 \text{ km/s} \) (corotation speed relative to Enceladus). Mainly water group ions (\( \text{O}^+ \), \( \text{OH}^+ \), \( \text{H}_2\text{O}^+ \), \( \text{H}_3\text{O}^+ \)).
CAPS ELS data for E3 - electrons must be distinguished from negative ions.

Negative nanograin

Photoelectrons in plume
Plume Particle Populations

• Positive (and negative) ions (H$_3$O$^+$), both from magnetosphere and locally produced.
• Suprathermal electrons (E$\approx$10eV) from magnetosphere and photoionization.
• Thermal electrons (2 eV) from thermalized suprathermals.
• Negative (and positive and neutral) nanograinns.
• Larger grains (negatively charged).
Plume Particle Populations contd.

- Neutral density $\approx 10^8 \text{ cm}^{-3}$ at $r \approx 2-3 R_{\text{enc}}$.
- Ion density $\approx 80 \text{ cm}^{-3}$ outside and 1000 - 10000 cm$^{-3}$ inside.
- Electron density $\approx 80 \text{ cm}^{-3}$ outside and 20 cm$^{-3}$ inside.
- Suprathermal electron ($> 10 \text{ eV}$) density $\approx 1 \text{ cm}^{-3}$.
- Negative nanograin density $\approx 10^3 \text{ cm}^{-3}$.
- Larger grains (micron), density $\approx 10^{-7} \text{ cm}^{-3}$. 
Saturn

L=4 magnetic field line

Less Dense Extended Neutral Torus

Dense Enceladus Neutral Torus near 4 Saturn radii
Extended Torus Suprathermals (and thermal electrons): Data (Schippers et al., 2009 - CAPS ELS) and Model (Cravens et al., 2011).
Electrons In Torus and Plume

• Two electron populations (hot and cold) are evident in Saturn’s inner magnetosphere (Voyager and Cassini data).

• (1) **Cold** -- recent data: Cassini RPWS/LP electron temperatures of 1-3 eV near L ≈ 4 (Gustaffson and Wahlund, 2010).

• (2) **Hot** -- suprathermal electrons with a photoelectron component observed by the Cassini CAPS ELS (Schippers et al., 2009).
Processes - Suprathermal Electrons

- Creation of photoelectrons by photoionization of neutrals by solar radiation
- Transport along magnetic field
- Elastic scattering
- Collisions: ionization (secondary electrons)
- Collisions: electronic excitation
- Collisions: rotational and vibrational excit.
- Coulomb collisions - heat thermal electrons
- (collisions with neutral and charged grains)
Model Cases for Plume 2-Stream Code

• *External electrons inputs:*
  • (1) zero incident flux at outer boundary
  • (2) torus model electron spectrum used as boundary condition

• *Surface Boundary Conditions*
  • (1) all electrons absorbed
  • (2) all electrons reflected
Fluxes Away from Enceladus (Upward) at R=2992.5 km for a Reflecting Field Line

- Solar HeII 30.4 nm Radiation absorption
- Model 1 - No Magnetospheric Electron Input
- Model 2 - Extended Torus Input

Electron Flux ($\text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1} \text{sr}^{-1}$)

Energy (eV)
Modeled Electron Fluxes at 802.5 km for a Reflecting Field Line Compared With E5 Measurement

- **Extended Torus Input**
- **No External Magnetospheric Input**
- **Model 1 Up Flux**
- **Model 2 Up Flux**
- **Model 1 Down Flux**
- **Model 2 Down Flux**

**CAPS - ELS - Anode 2, Oct 9, 2008, 19:07:39 UT**

- **Electron Flux (cm\(^{-2}\) s\(^{-1}\) eV\(^{-1}\) sr\(^{-1}\))**
- **Energy (eV)**

- Maxwellian \(n_e=30\) cm\(^{-3}\), \(kT_e = 1.8\) eV

- 1 count instr. trigger
Plume Electron Conclusions

- Photoelectrons produced by solar radiation from the plume gas are important within a few $R_{\text{enc}}$.
- The energy spectra look similar to the torus electron spectra - photoelectrons from solar ionization of neutrals.
- External inputs (i.e., torus electrons) also seem to be important outside of a few $R_{\text{enc}}$ but not near the surface where the mean free path is small.
- *Role of grains? Beams?*
Electron Absorption by Nanograin?

- Grain absorption should affect the electron spectrum if $n_d \sigma_d$ is equal to, or exceeds $n_g \sigma_g$. For nanograin this translates to $n_d / n_g > 0.003$.
- Or $n_d > 10^5 \text{ cm}^{-3}$ (Hill et al., $10^3 \text{ cm}^{-3}$).
- But low energy electrons could be affected much more than suprathermal electrons.
- UV absorption by grains (and grain photoelectron production) could also affect the suprathermal electron electron spectrum in the plume.
Plasma-Grain Processes

• Photon + d --> d⁺ + e
• n⁺ + d ----> d⁺ (or d⁻ for energetic ion)
• e + d ----> d⁻ (important)
• e + d⁻ <----> e + d⁻ (scattering)

• Our calculations show that grains cannot have important effects on hot, suprathermal electrons, but..

• Electron depletion in plume plus presence of negative nanograins indicates that colder ("thermal"?) electrons must collide with grains and are probably trapped (polarization electric field?) in the plume.
Plume Particle Populations

Enceladus

- e
- n
- d
- n+
- photon

Connections:
- e → n
- n → d
- d → n
- n+ → e
- photon → e

Arrows indicate transitions or interactions between particle populations.
Plasma-Grain Process Times

- convection time \( \approx \frac{2R_{\text{enc}}}{u} \approx 20 - 3 \times 10^2 \text{ s} \)
- parallel elec transp \( \approx \frac{3R_{\text{enc}}}{u_e} \approx 1 \text{ s} \)
- nanograin transport time \( \approx \frac{3R_{\text{enc}}}{u_d} \approx 1000 \text{ s} \)
- ion charge exchange \( \approx \frac{1}{n_n v \sigma_{\text{cx}}} \approx 10 \text{ s} \)
- 20 eV inelastic elec-neutral \( \approx 1 \text{ s} \)
- 2 eV inelastic elec-neutral \( \approx 10 - 30 \text{ s} \)
- 2 eV elastic elec-neutral \( \approx 0.2 \text{ s} \) (300 s diffusion transport time)
- elec-nanograin coll time \( \approx 300 \text{ s} \)
- nanograin charging time \( \approx \frac{e}{I_e} \approx 10^4 \text{ s} \)
- ion density prod time \( \approx \frac{n_i}{\ln n} \approx 10^3 \text{ s} \)