# Cold plasma in the jovian system

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# JuMMP Investigation



- Jupiter Magnetosphere and Moons Plasma assessment study.

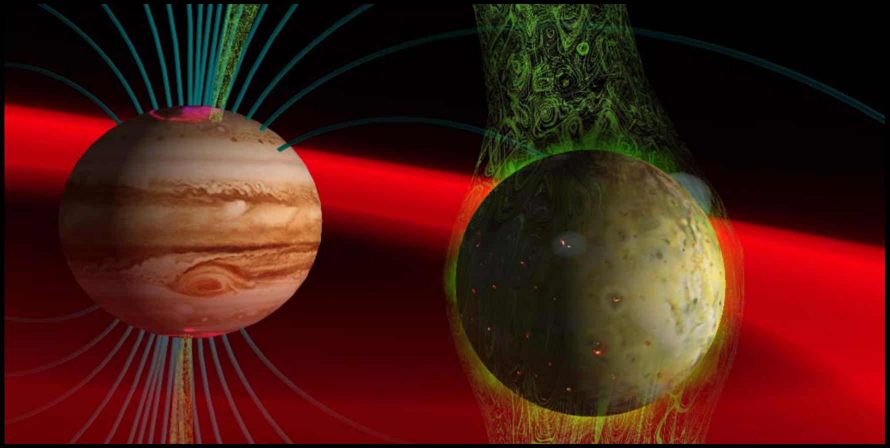
- Exceptionally strong science study team:
  - >30 year heritage in studying rapidly rotating magnetospheres and moon-magnetosphere interactions.
  - >40 year heritage in space plasma physics.
  - Theory, empirical modelling, simulation and observation.
  - Includes team members that have been involved in important recent discoveries at Jupiter and Saturn.

- Consortium has strong links with magnetometer, plasma wave, and UV teams and long-standing collaborations with many members in the PEP consortium.

- Strongly involved with JSDT and working groups.

# Contents

- The jovian magnetosphere and its plasma populations
- Cold plasma:
  - Solar wind and magnetosheath
  - Io plasma torus
  - Cold plasma in the magnetodisc and outer magnetosphere
  - Cold plasma in trans-Io/Europa/Ganymede/Callisto environment
- Cold plasma models
- Key science questions
- Implications for surface charging



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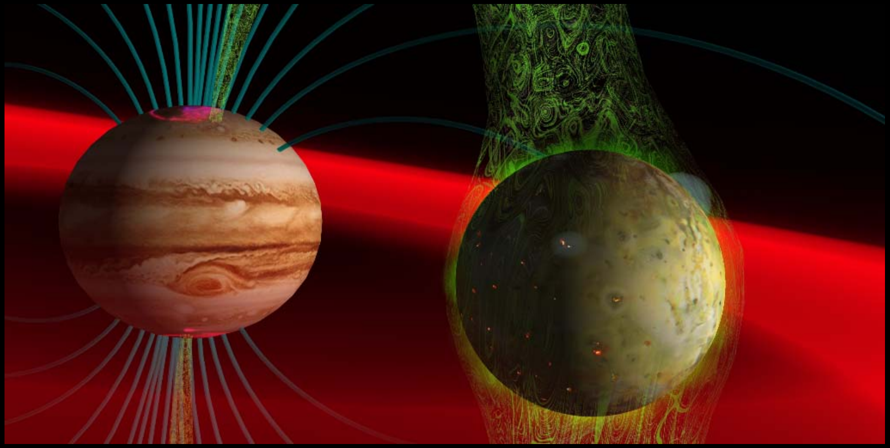


# Introduction



- Hot plasma populations (>~10 keV) provide most of the particle pressure in the jovian magnetosphere.

- However, cold plasma (<~10 keV) carries most of the density.

- Important for surface charging….
  - Thermal charging currents for electrons and ram currents for ions.
  - Secondary electron emission currents from electron and ion impact.

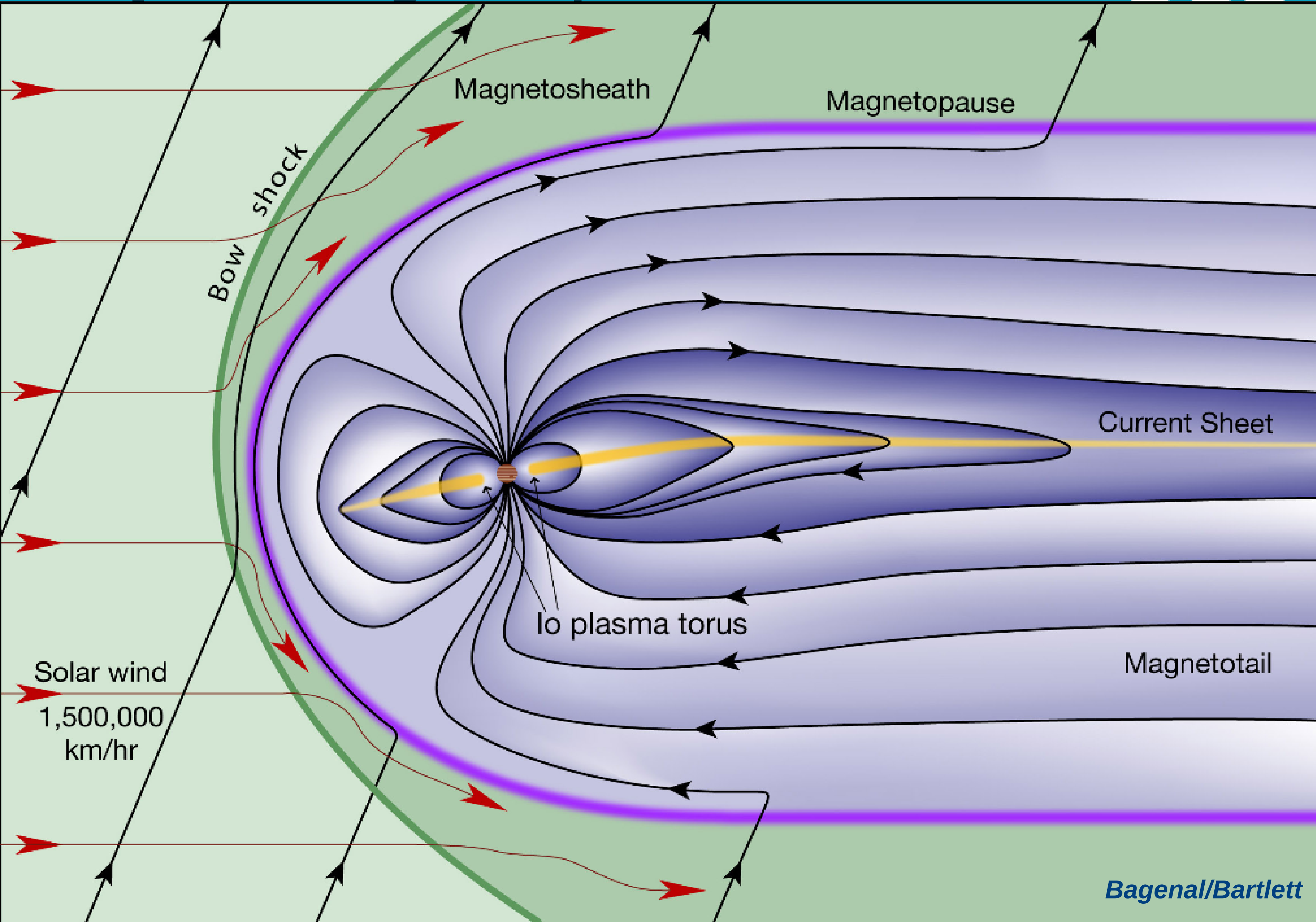
- As well as for the physics of the system…
  - Centrifugal stresses and latitudinal plasma/current sheet structure.
  - Seed populations for hot plasma and radiation belt distributions.
  - Ram pressures and wave speeds.

- Jupiter's environment has been visited by **eight** spacecraft !!

- In this talk I will (rather arbitrarily) consider cold plasma to be "measured" at less than a few 10s of keV/charge.

# The jovian magnetosphere





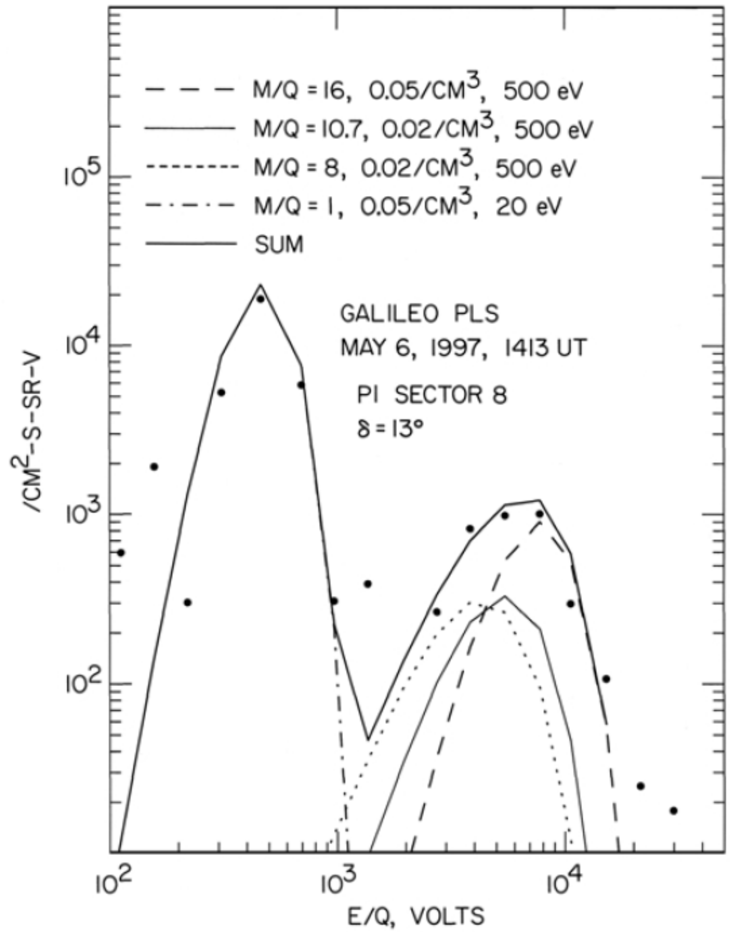

*Bagenal/Bartlett*

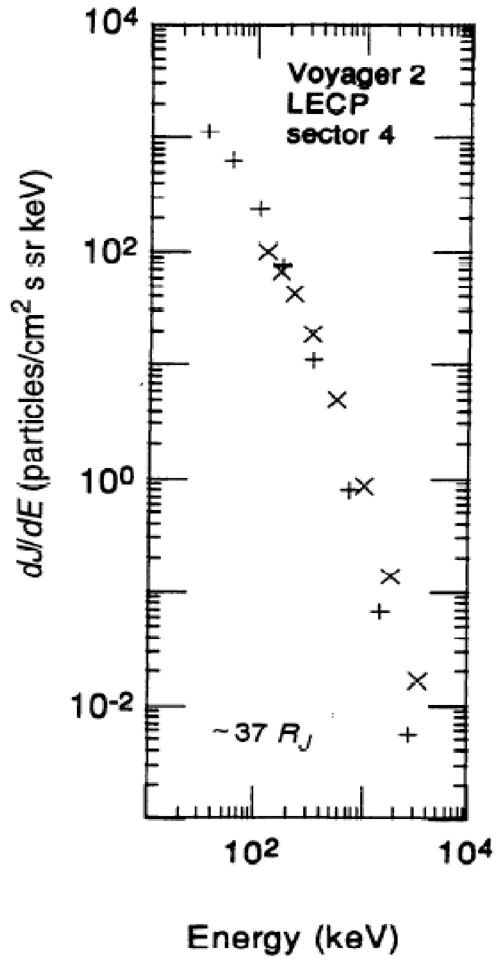
# Plasma in the jovian magnetosphere

- Distinct populations: cold plasma, hot plasma, radiation belt particles

- Cold plasma: $k_B T \sim 1\text{-}1000$ eV
- Hot plasma: $k_B T \sim 10\text{-}100$ keV

*Frank et al. (2002)*




*Kane et al. (1996)*

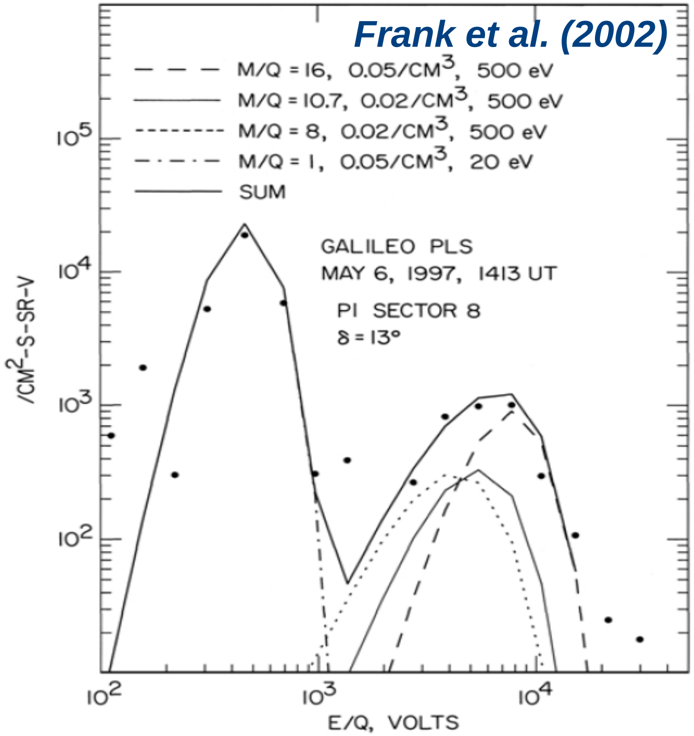
# Cold plasma in Jupiter's magnetosphere

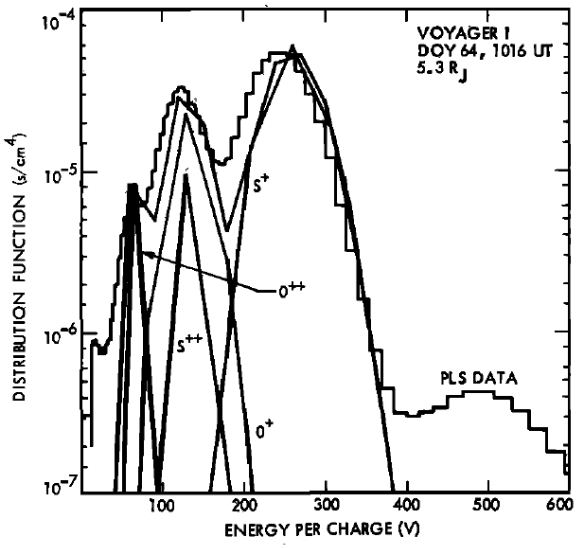


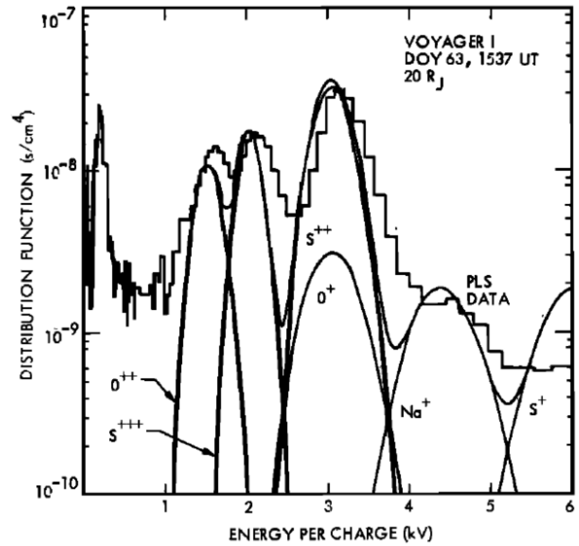
- Ions:
  - Thermal energies less than 1 keV.
  - Often measured at several kV due to the bulk velocity (several 100 km s$^{-1}$) of these populations.

- Electrons:
  - Thermal energies less than several keV.
  - Have little knowledge of distributions above 6 keV.

*Frank et al. (2002)*




*Divine and Garrett (1983)*

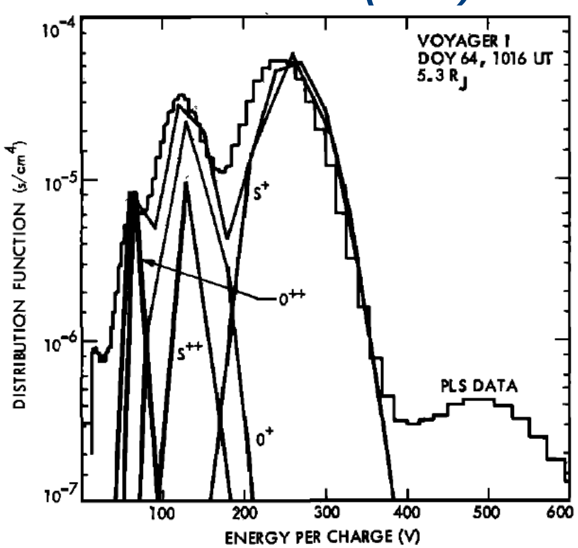
# Plasma composition

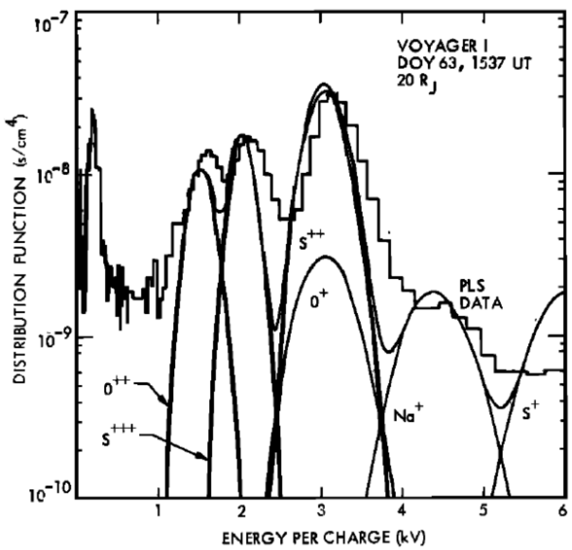


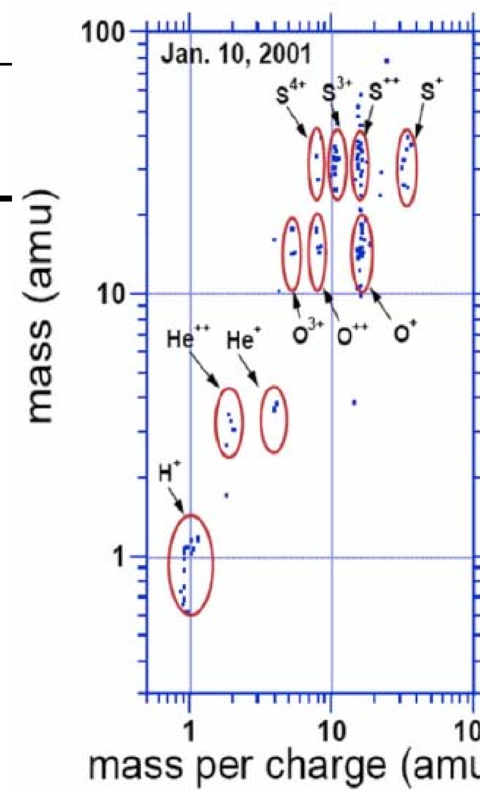
| | |
|---|---|
| Solar wind | $H^+$, $He^{2+}$, $O^{6+}$ |
| Jupiter | $H^+$, $(H2^+, H3^+)^+$ |
| Io | $O^+$, $O^{2+}$, $O^{3+}$, $(O^{4+})$, $(Na^+, K^{2+})$, $S^+$, $S^{2+}$, $S^{3+}$, $S^{4+}$, $(S^{5+})$ |
| Icy satellites | $(H_2O^+, H_3O^+)$, $(H^+, H_2^+, O^+, O_2^+$, $S_x^+$, $SO_x^+$, $CO_x^+$, $Na^+$, $K^+$, $Cl^+$, $Cl^-$, possibly $Mg^+$, $Ca^+$ and organic fragment ions) |
| Undetermined (possibly Jupiter) | $He^+$ |

*Geiss et al. (1992)*

*Divine and Garrett (1983)*



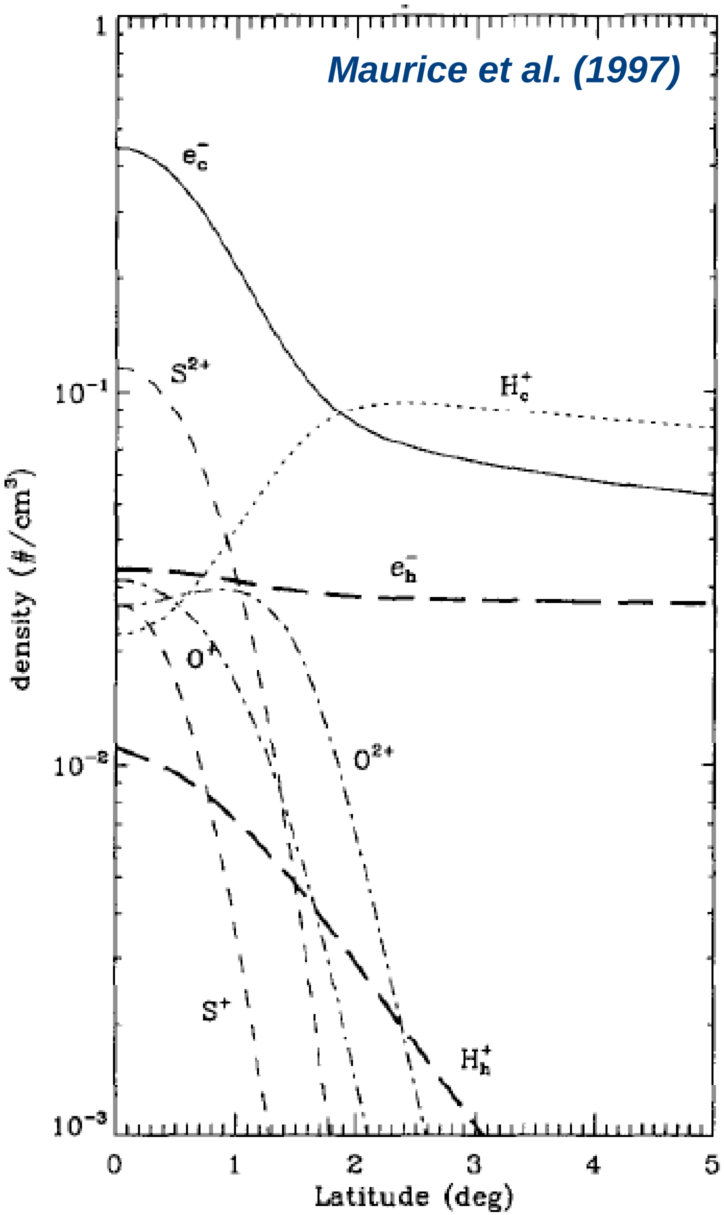




*After Hamilton et al. (2001)*

# Effects of centrifugal force



- Rapid rotation of the magnetosphere $\Rightarrow$ important centrifugal forces.
- Centrifugal scale heights $\propto (kT/m)^{1/2}$.
  - Heavy cold species are confined to the equator - electrons can fill field lines.
- Quasi-neutrality $\Rightarrow$ ambipolar electric field which pulls $e^-$ towards equator
- Simple case for single ion and electron population.
- Complex latitudinal distribution with multiple species and multiple charge states.



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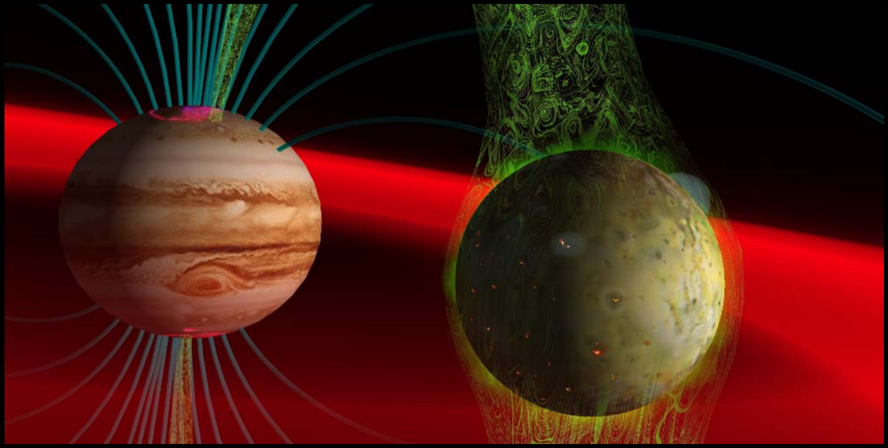
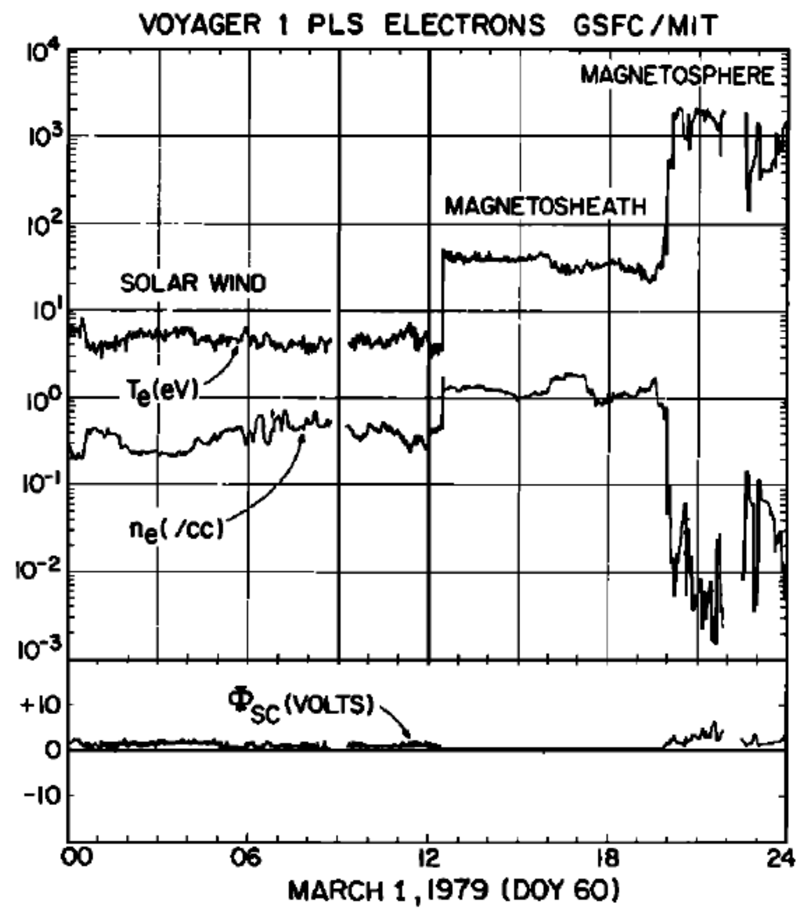


# Solar wind and magnetosheath

- Solar wind (at least core) and magnetosheath populations are cold populations.

- Solar wind:
  - $n_e$=2-8×10$^5$ m$^{-3}$ (0.2-0.8 cm$^{-3}$)
  - $T_e$=3-9 eV
  - $T_e/T_p$=2.5 ⇒$T_p$~7-23 eV
  - $v_{SW}$=400 km s$^{-1}$
  - Suprathermal (halo) $T_e$~40 eV

- Magnetosheath:
  - $n_e$=0.9-2×10$^6$ m$^{-3}$ (0.9-2.0 cm$^{-3}$)
  - $T_e$=20-50 eV (mean energy 40-60 eV)
  - Suprathermal $T_e$~keV




*Scudder, Sittler and Bridge (1981)*

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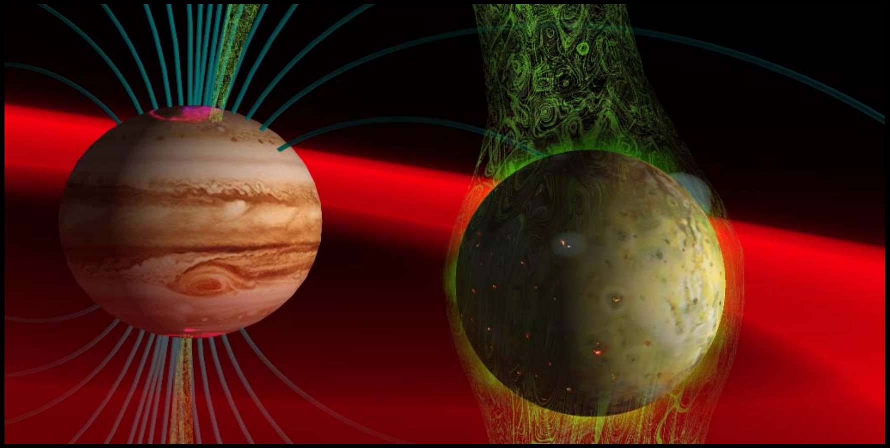
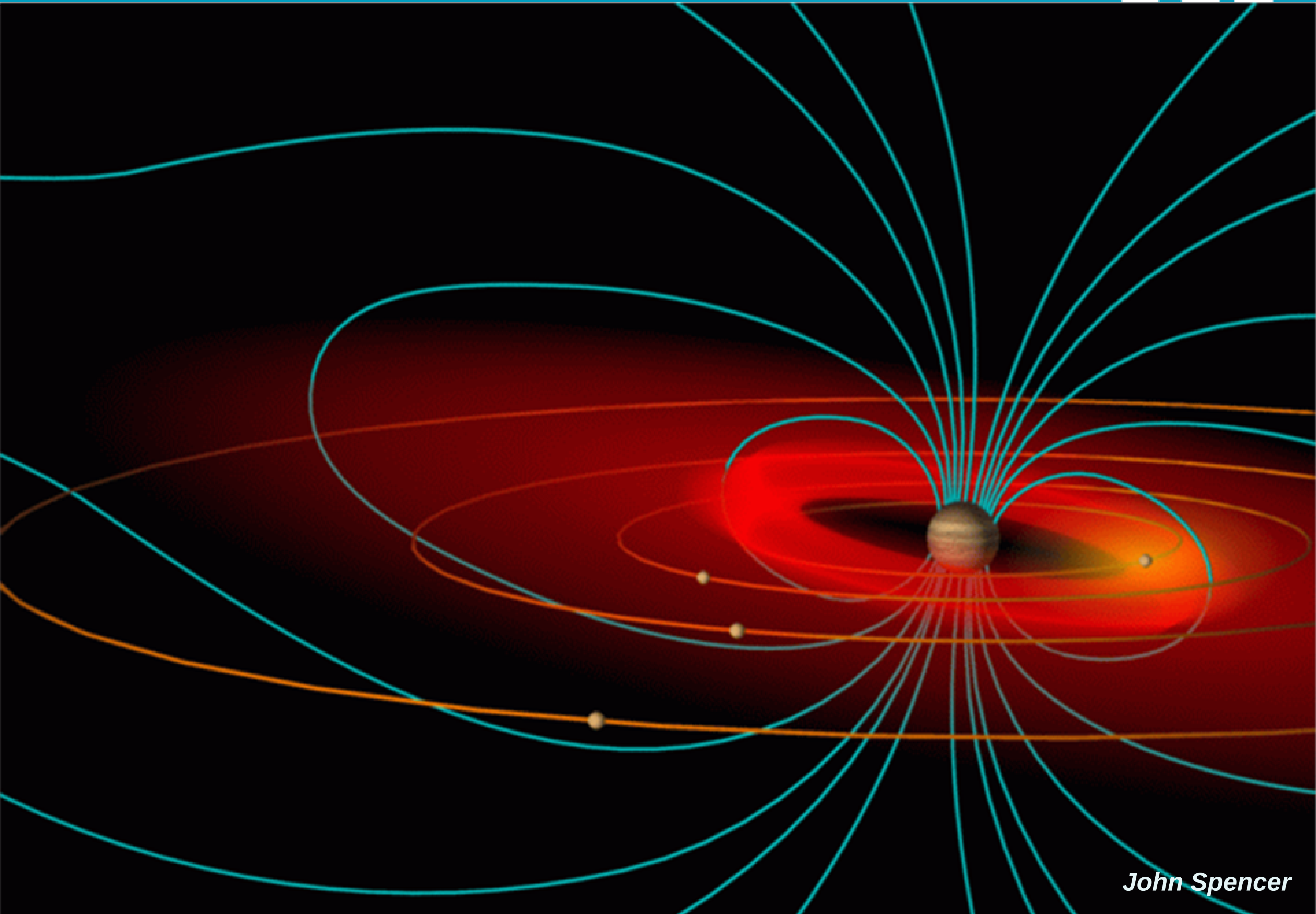
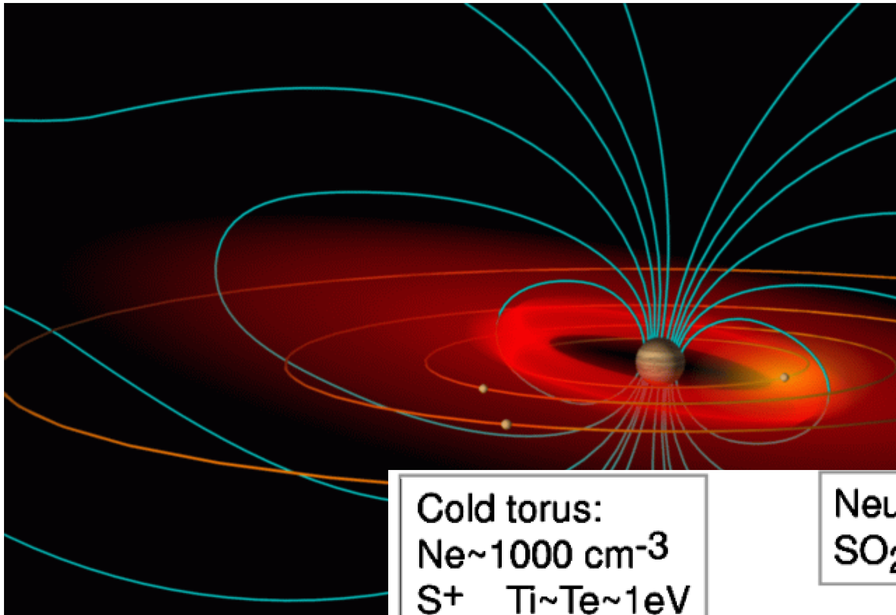


# Plasma torus

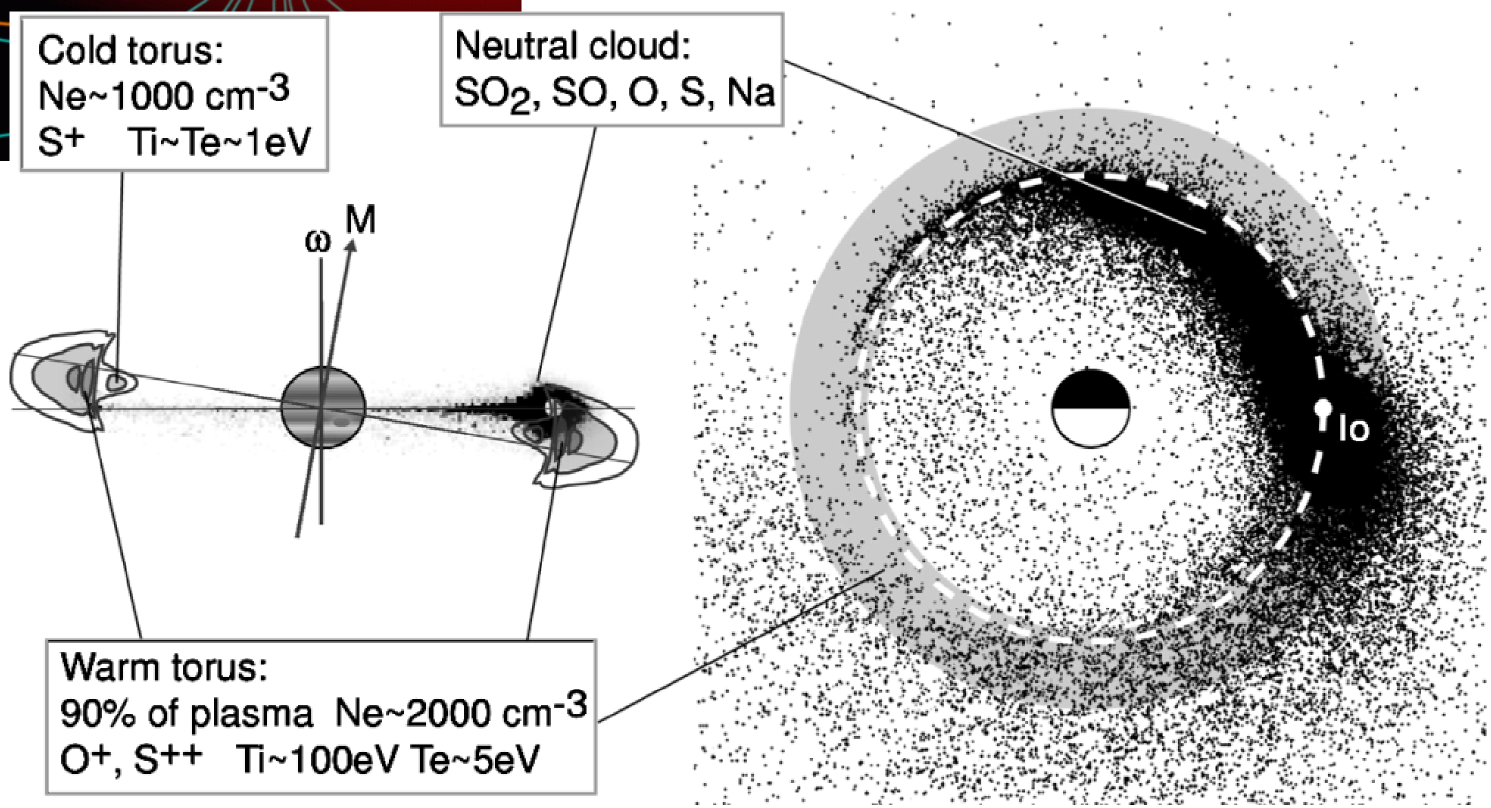


# Plasma torus





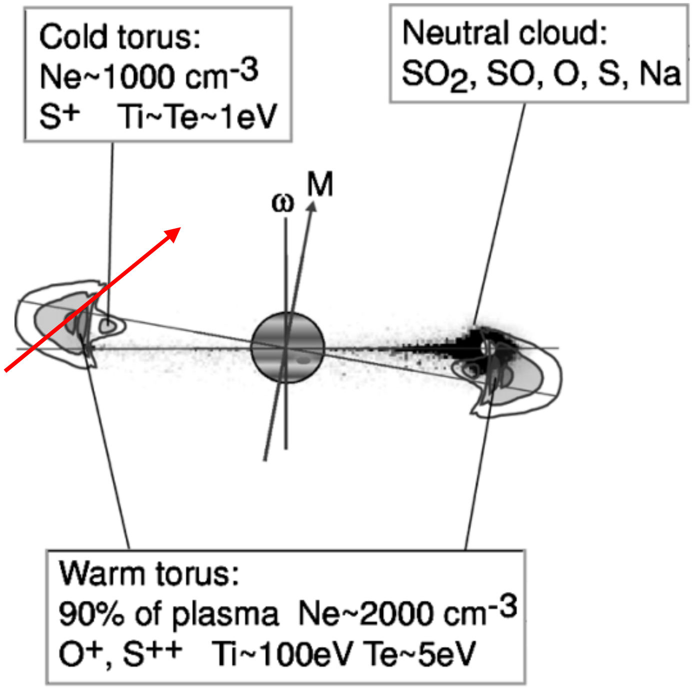
- Neutral cloud in equatorial plane.
- Cold and warm plasma torii located in the centrifugal equator.
- Centrifugal equator located between equator and magnetic dipole equator.




Thomas et al. (2004)

# Plasma torus

- Spacecraft only make cuts through this 3D picture.
- Solve force balance along field lines (diffusive equilibrium) to extrapolate local measurements and generate 2D maps of density.
- Require:
  - Ion composition [UV spectra].
  - Ion and electron temperatures and anisotropies [Voyager/PLS].
  - Measured densities [Voyager/PLS & PWS].

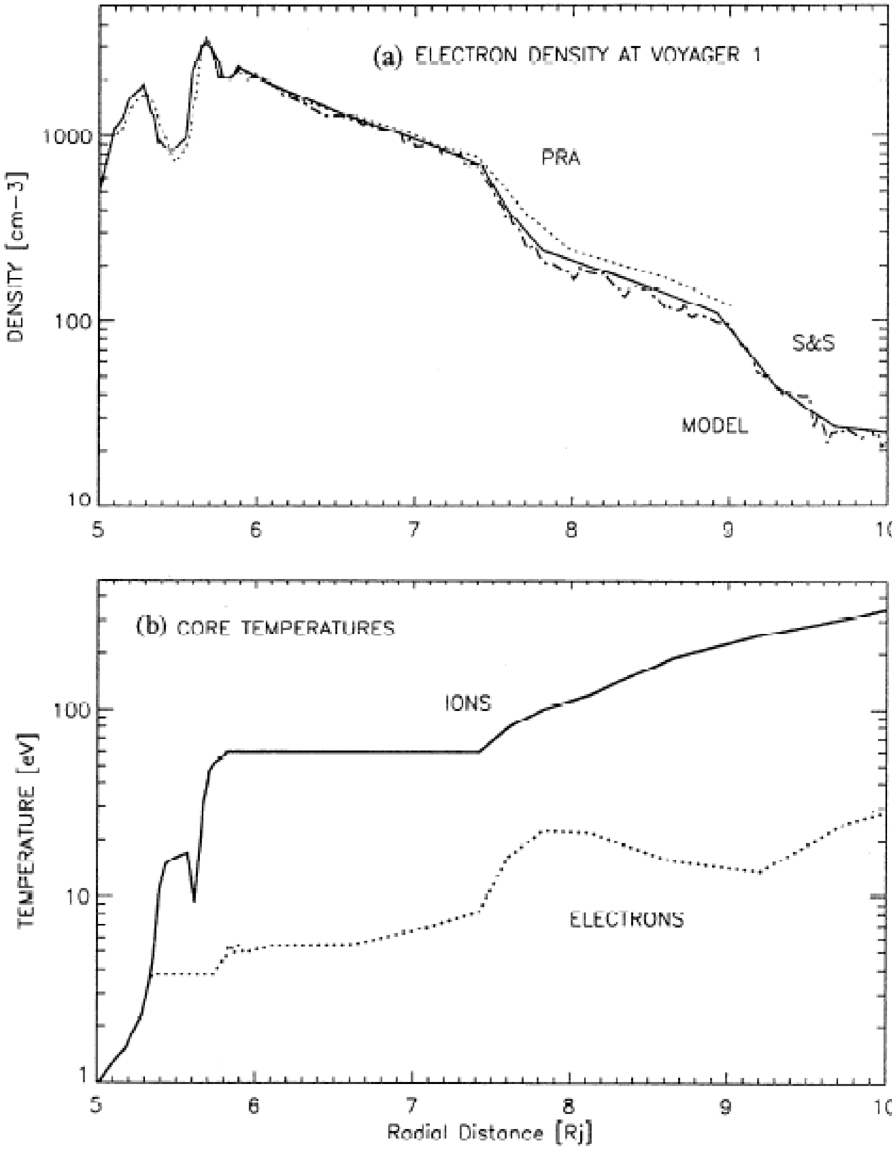



- Carried out by Bagenal and Sullivan (1981) - later discovered that input ion temperatures were in error by a factor of 2.
- Corrected in later calculations (Bagenal et al., 1984; 1994).

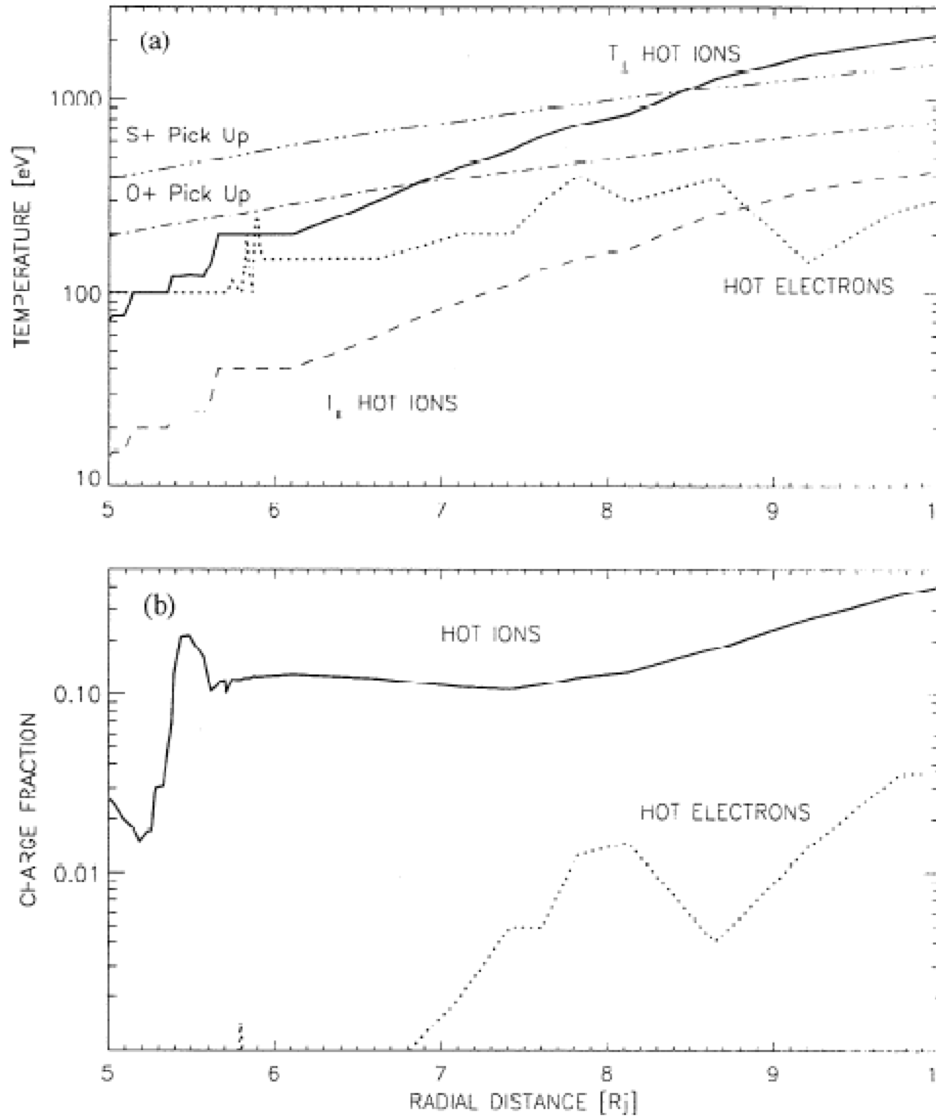
# Plasma inputs



## Thermal inputs



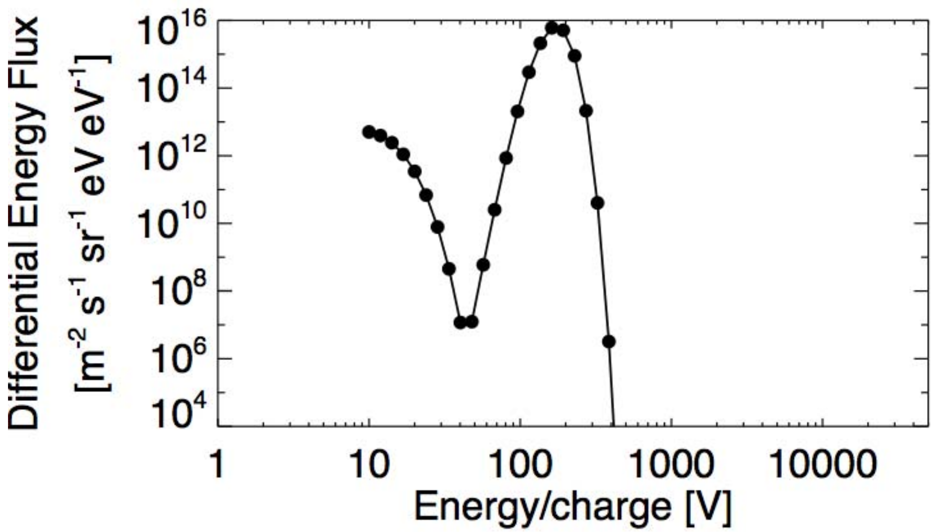

## Suprathermal inputs

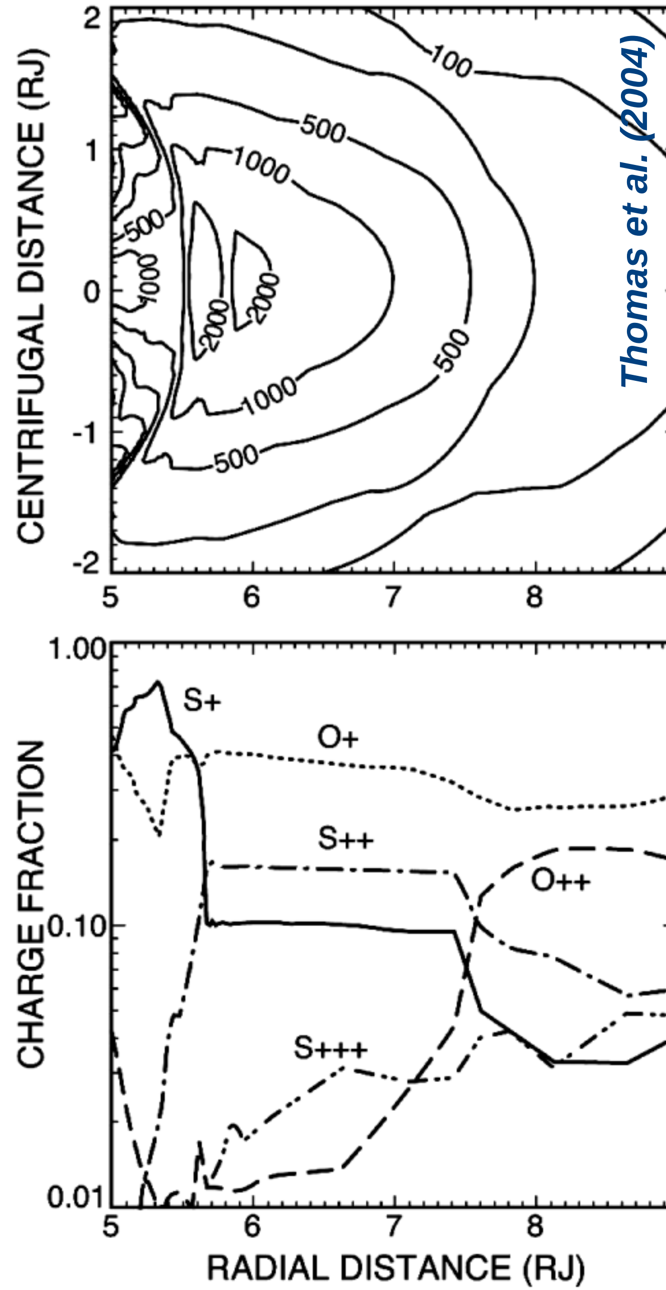



*Bagenal (1994)*

# 2D Maps and composition

- Electron density maximises around $2 \times 10^9$ m$^{-3}$.
- Evolution in dominant ion species.
- $H^+$ is a minor species in the plasma torus, but is more important in the outer magnetosphere.
- $H^+$ E/Q spectra from the cold torus often appear below the 10 eV threshold of V/PLS.




*Thomas et al. (2004)*

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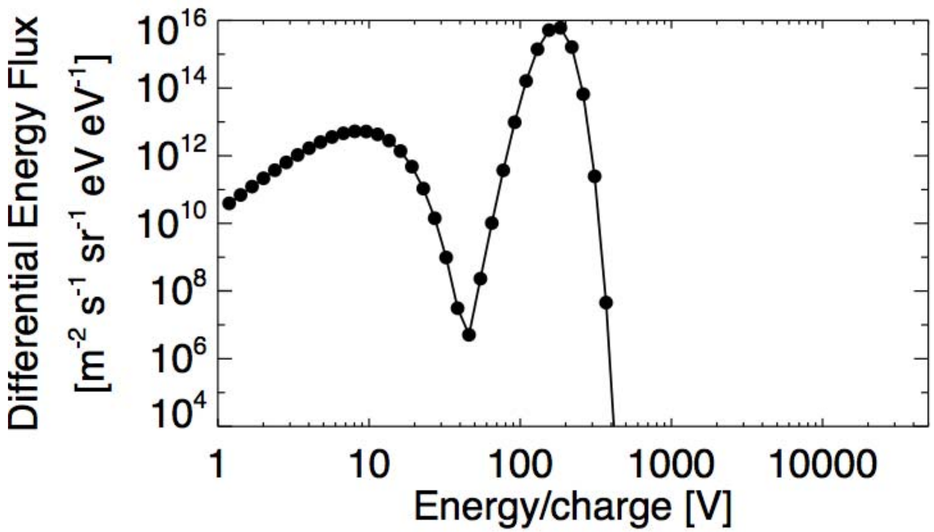


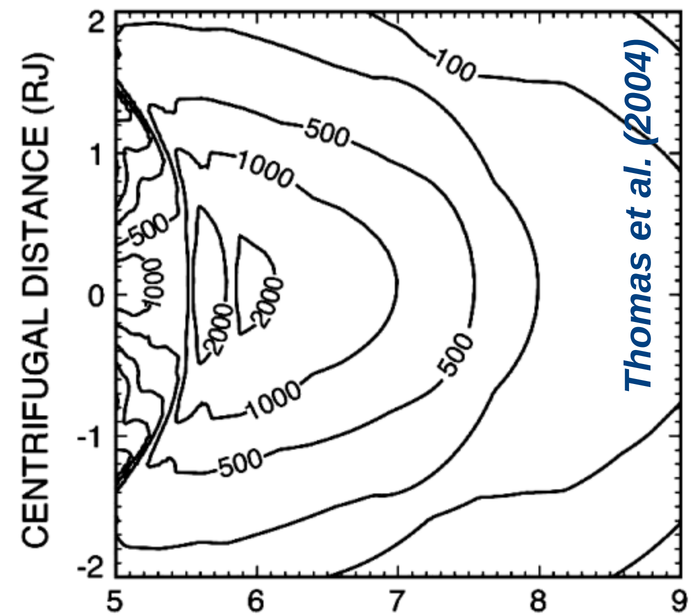


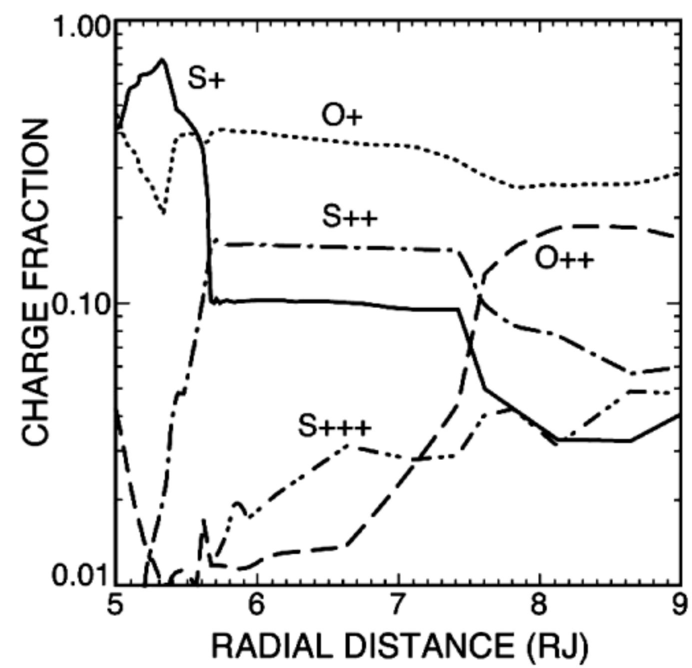

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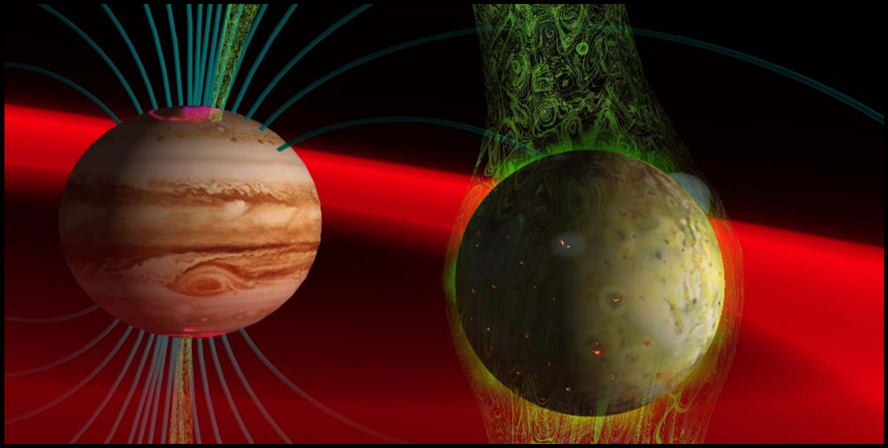
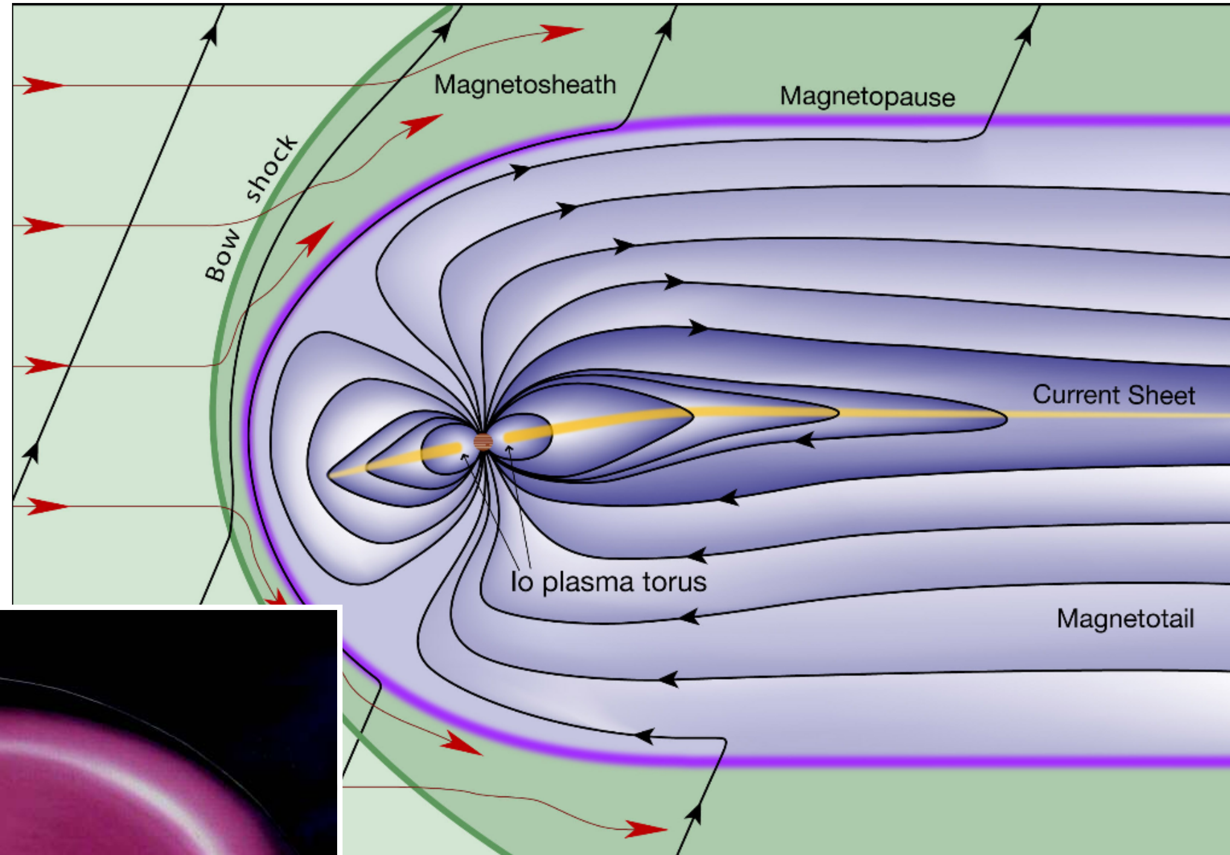
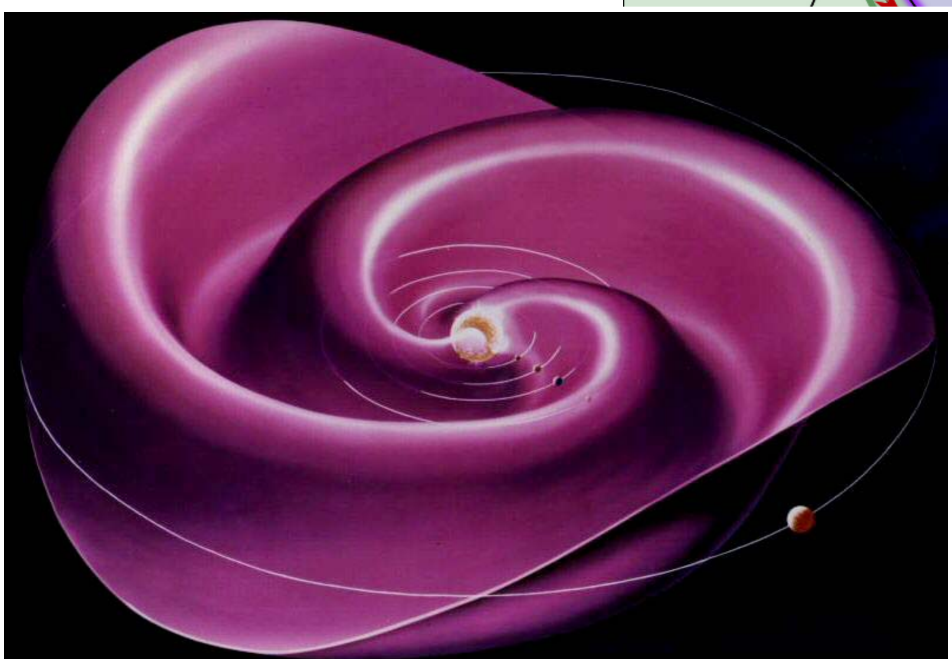


# Magnetodisc morphology





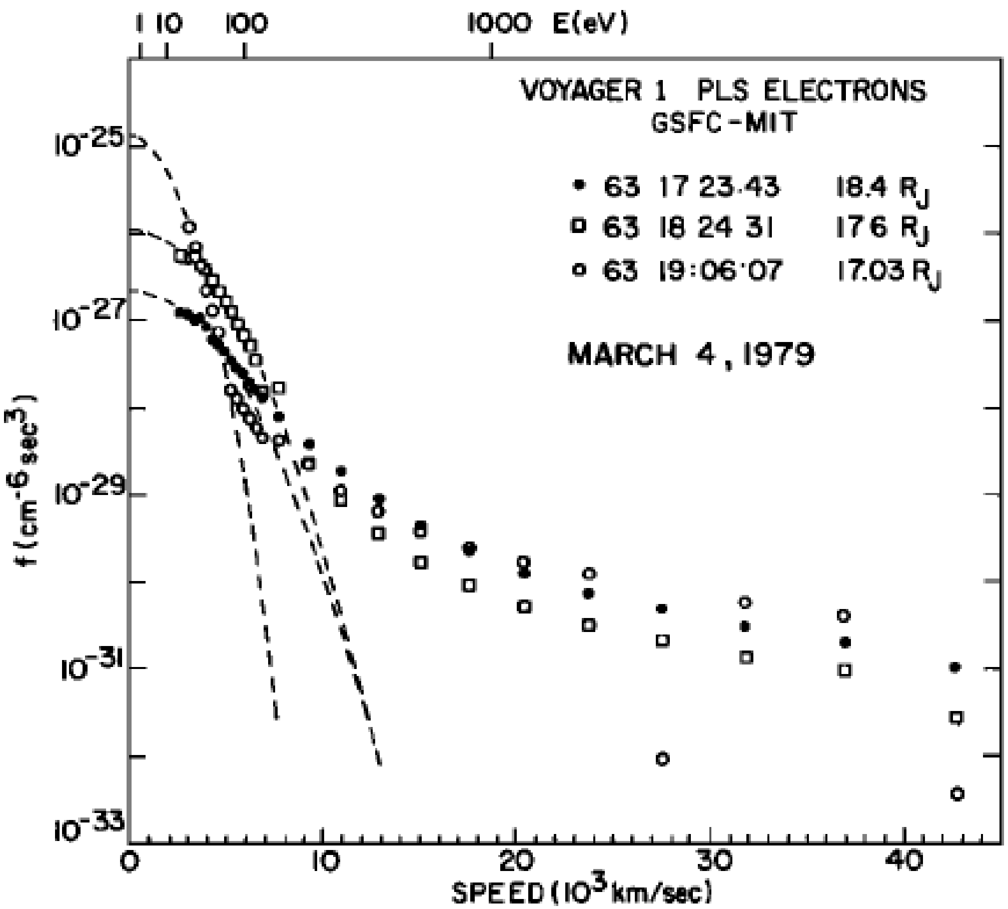



- Models give $z_{cs}$ as function of System III longitude, local time, and radial distance.
- Latest model: *Khurana and Schwarzl (2005)*.

# Electrons in the middle magnetosphere



- Scudder, Sittler and Bridge (1981) published significant analyses of the Voyager/PLS electron data.
- Voyager/PLS data up to 6 keV - Voyager/LECP starts at 28 keV.
- Core Maxwellian population with suprathermal tail - Kappa or bi-Kappa




*Scudder, Sittler and Bridge (1981)*

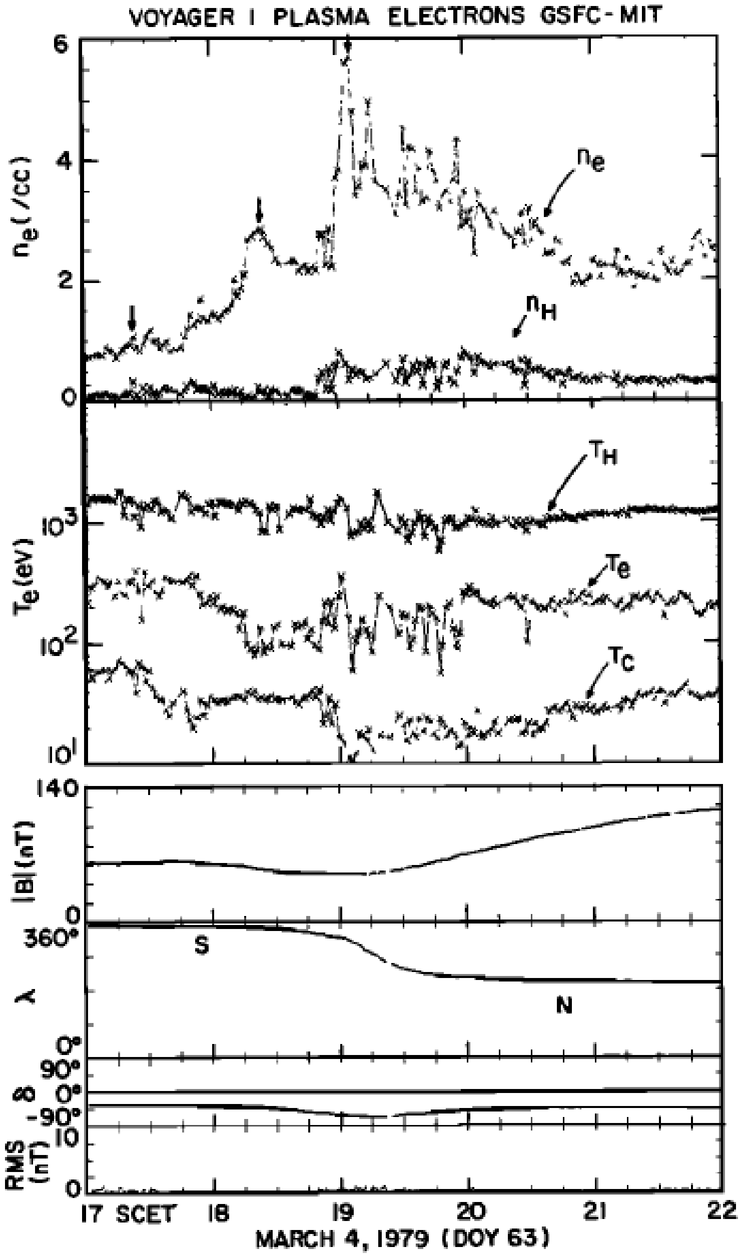
- Limited published data from Galileo/PLS (failure of electron sensor below ~ few keV)

- Little information available to close gap in understanding of the electron distribution between 6 and 28 keV.

# Electrons at CS crossing

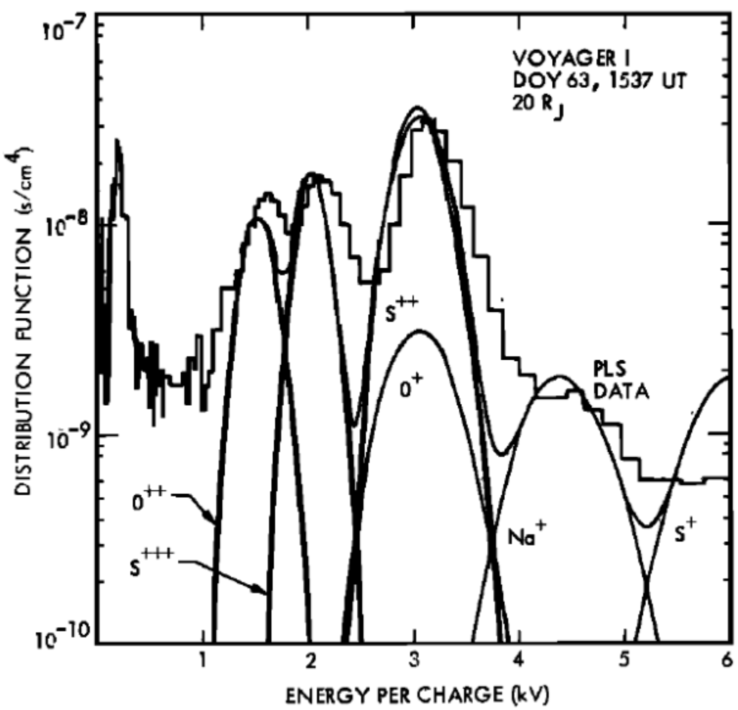


- Densities vary between ~$10^3$ and ~$10^5$ $m^{-3}$.
- Temperatures between ~0.1 and 3 keV.
  - Range probably due to bi-modal or Kappa-distributed electrons.
  - $T_c$~10-80 eV
  - $T_h$~1 keV
  - $T_e \sim n_{e,c}T_c + n_{e,h}T_h/(n_{e,c}+n_{e,h})$
- Electron density maximises at current sheet crossings due to increase in cold electron density.
- Hot electron density almost constant.
- Occasional appearance of cold blobs of plasma - linked to plasma transport?

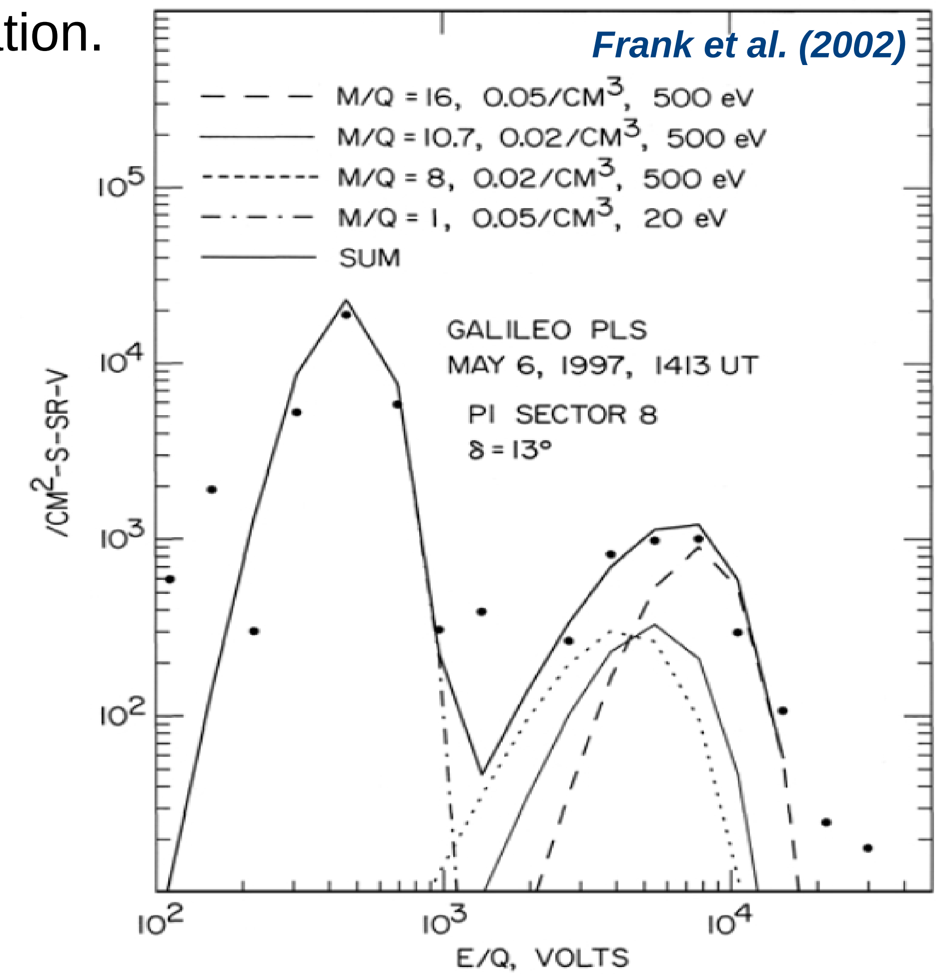


# Ion spectra

- Dominant species appear to be M/Q=16 (either S++ or O+) and M/Q=1 (H+) - M/Q=8 (O++) and 10.7 (S+++) are more minor species.
- Cold populations $T_{H+}$=20 eV and $T_{O/S}$=500 eV but measured at kV due to bulk motion (supersonic).
- Evidence of hot ~10 keV H+ population.



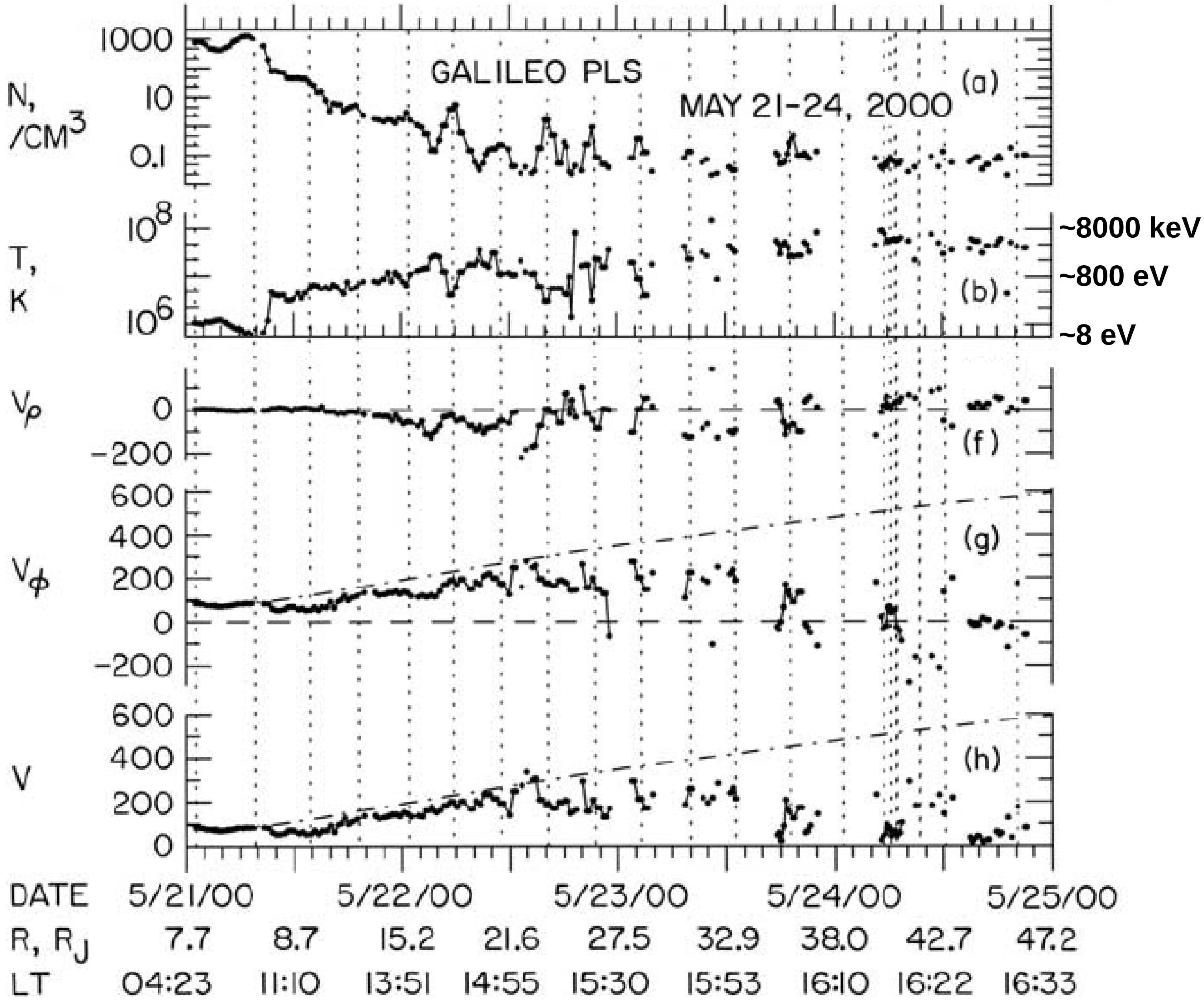

*Divine and Garrett (1983)*




*Frank et al. (2002)*

# Ion moments





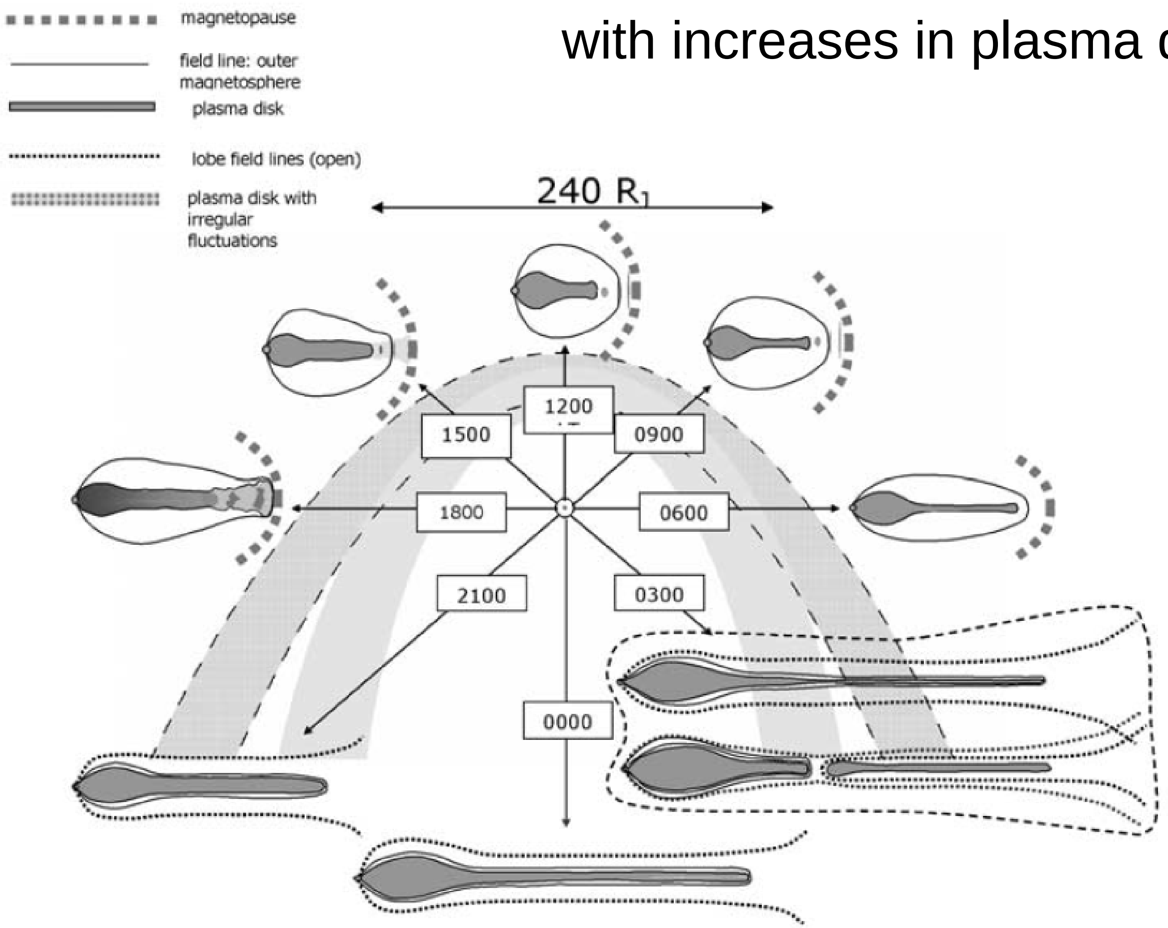

*Frank et al. (2002)*

# Outer magnetosphere



- Characterised by disordered plasma - c.f. New Horizon's observations in the deep magnetotail.

- Cushion region: Dayside region characterised by southward fields and numerous field "nulls" associated with increases in plasma density.




*Kivelson and Southwood (2005)*

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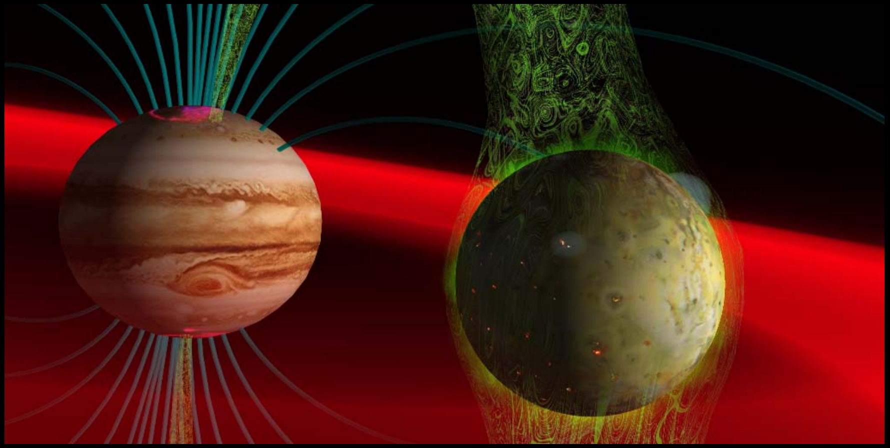

# Trans-moon cold plasma environments



**Table 21.1.** Physical properties of the Galilean satellites and surrounding plasma.

| Symbol (units), Physical property | Io | Europa | Ganymede | Callisto |
|---|---|---|---|---|
| *Plasma and field parameters of the ambient magnetospheric plasma* | | | | |
| $B_o$(nT), jovian magnetic field, av. min (max) | 1720 (2080) | 370 (460) | 64 (113) | 4 (42) |
| $n_e$(elns cm$^{-3}$), Eq. av. (range) eln. density | 2500 (1200–3800) | 200 (18–250) | 5 (1–10) | 0.15 (0.01–0.70) |
| $< Z >$, Eq. av. (lobe) ion charge | 1.3 (1.3) | 1.5 (1.5) | 1.3 (1) | 1.5 (1) |
| $< A >$, Eq. av. (lobe) ion mass in $m_p$ | 22 (19) | 18.5 (17) | 14 (2) | 16 (2) |
| $n_i$(ions cm$^{-3}$), av. (range) ion no. density | 1920 (960–2900) | 130 (12–170) | 4 (1–8) | 0.10 (0.01–0.5) |
| $\rho_m$(amu cm$^{-3}$), av. (range) ion mass density | 42 300 (18 000–64 300) | 2500 (200–3000) | 54 (2–100) | 1.6 (0.02–7) |
| $kT_i$ (eV), equator (range) ion temperature | 70 (20–90) | 100 (50–400) | 60 (10–100) | 60 (10–100) |
| $kT_e$(eV), electron temperature | 6 | 100 | 300 | 500 |
| $p_{i,th}$(nPa), Eq. (range) pressure thermal plasma | 22 (3–42) | 2.1 (0.10–11) | 0.04 (0.002–0.12) | 0.001 (0.00–0.01) |
| $p_{i,en}$(nPa) (20 keV–100 MeV ions) | 10 | 12 | 3.6 | 0.37 |
| $p_e$(nPa) (both "cold" and "hot" electrons) | 2.4 | 3.2 | 0.2 | 0.01 |
| $p$(nPa), Eq. (max) total pressure | 34 (54) | 17 (26) | 3.8 (3.9) | 0.38 (0.39) |
| $v_{cr}$(km s$^{-1}$), local corotation velocity | 74 | 117 | 187 | 328 |
| $v_s$(km s$^{-1}$), satellite orbit velocity | 17 | 14 | 11 | 8 |
| $v_\phi$(km s$^{-1}$)s plasma azimuthal vel. (range) | 74 (70–74) | 90 (70–100) | 150 (95–163) | 200 (130–280) |
| $u$(km s$^{-1}$), relative velocity (range), $v_\phi t\ v_s$ | 57 (53–57) | 76 (56–86) | 139 (84–152) | 192 (122–272) |
| $v_A$(km s$^{-1}$), Eq. (range) Alfvén speed | 180 (150–340) | 160 (145–700) | 190 (130–1700) | 70 (30–6500) |
| $c_s$(km s$^{-1}$), Eq. (range) sound speed | 29 (27–53) | 92 (76–330) | 280 (190–1400) | 500 (230–4400) |
| $B_o^2/2\mu_o$(nPa), Eq. (lobe) magnetic pressure | 1200 (1700) | 54 (84) | 1.6 (5) | 0.006 (0.7) |
| $\rho u^2$(nPa), Eq. av. (max) ram pressure | 230 (350) | 24 (38) | 1.7 (4.1) | 0.10 (0.90) |
| $\rho u^2$(nPa), lobe ram pressure | 100 | 2.5 | 0.08 | 0.002 |

***Kivelson et al. (2004)***

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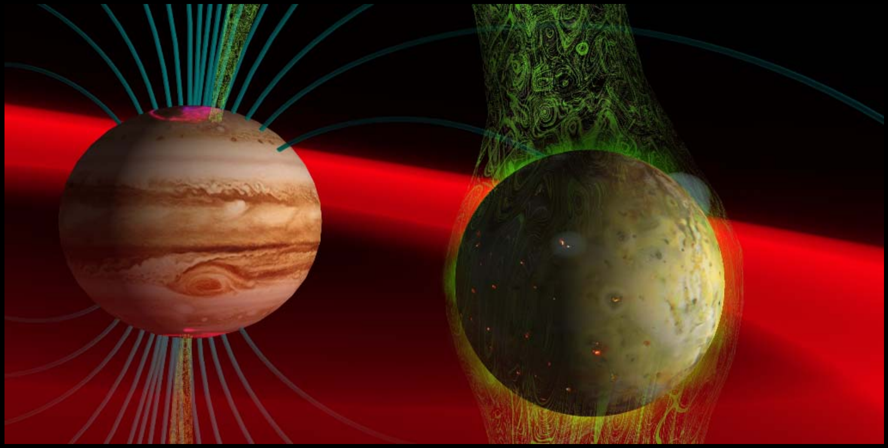

# Models



- *Divine and Garrett (1983)* model.
  - Uses incorrect ion reduction in Io PT and map has shown to be inconsistent with Ulysses data.
  - Assumes populations are isotropic drifting Maxwellians.
  - Fixed azimuthal plasma velocity with no local time asymmetries or local structure.
  - Old magnetodisc geometry model.

- Revisions:
  - New magnetodisc morphology (*Khurana and Schwarzl, 2005*).
  - Lots more data and "meta-models" (e.g., *Bagenal, 1994*; *Moncuquet et al., 2002*) available now on which to base a new cold plasma model.
  - However, Voyager and Ulysses electron data sets remain the most complete and published low energy electron data at Jupiter.
  - Critical to consider the possible impacts of this - i.e., will s/c potential calculations in JOREM/Spenvis be incorrect?

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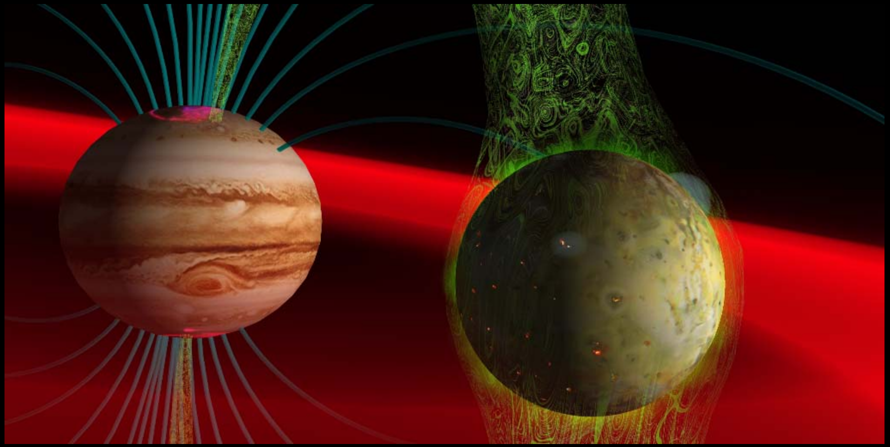
- Implications for surface charging



# Some key cold plasma science questions



- How is iogenic plasma accelerated from ~1 eV to >100 keV ?
  - E.g., stochastic acceleration, turbulence, and Speiser-type acceleration.

- What is the role of the solar wind in driving and shaping the jovian magnetosphere?
  - Track ion velocity, composition and temperature of different flows.

- What is the cushion region and how is it formed?

- How is plasma transported from the Io PT and through the magnetodisc?

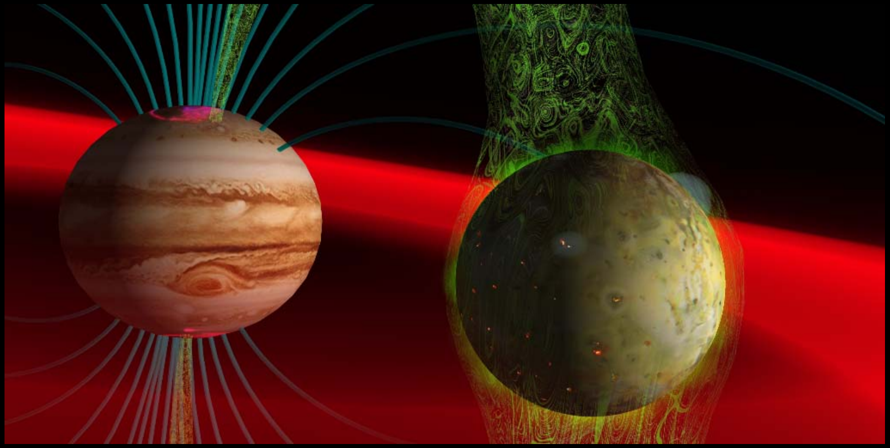
- How is cold plasma lost from the magnetosphere?
  - All lost in the tail - or ejection through the dayside magnetopause?
  - Tearing in the magnetodisc?

- What is the nature of plasma flow around Ganymede’s magnetosphere?

- Magnetospheric stress balance: what roles do centrifugal stress and cold plasma anisotropies play?

# Contents

- The jovian magnetosphere and its plasma populations
- Cold plasma:
  - Solar wind and magnetosheath
  - Io plasma torus
  - Cold plasma in the magnetodisc and outer magnetosphere
  - Cold plasma in trans-Io/Europa/Ganymede/Callisto environment
- Cold plasma models
- Key science questions
- Implications for surface charging



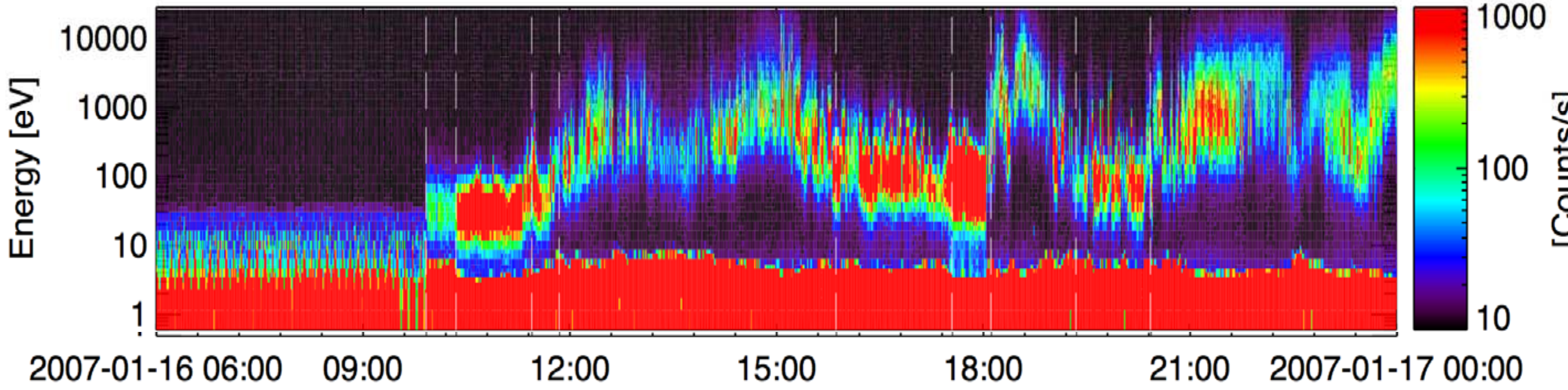
# Spacecraft charging



- Figure below shows Cassini CAPS/ELS data from a period where the spacecraft was charged to a positive potential.

- Changes in potential with ambient conditions clearly visible: 3 - 40 V.

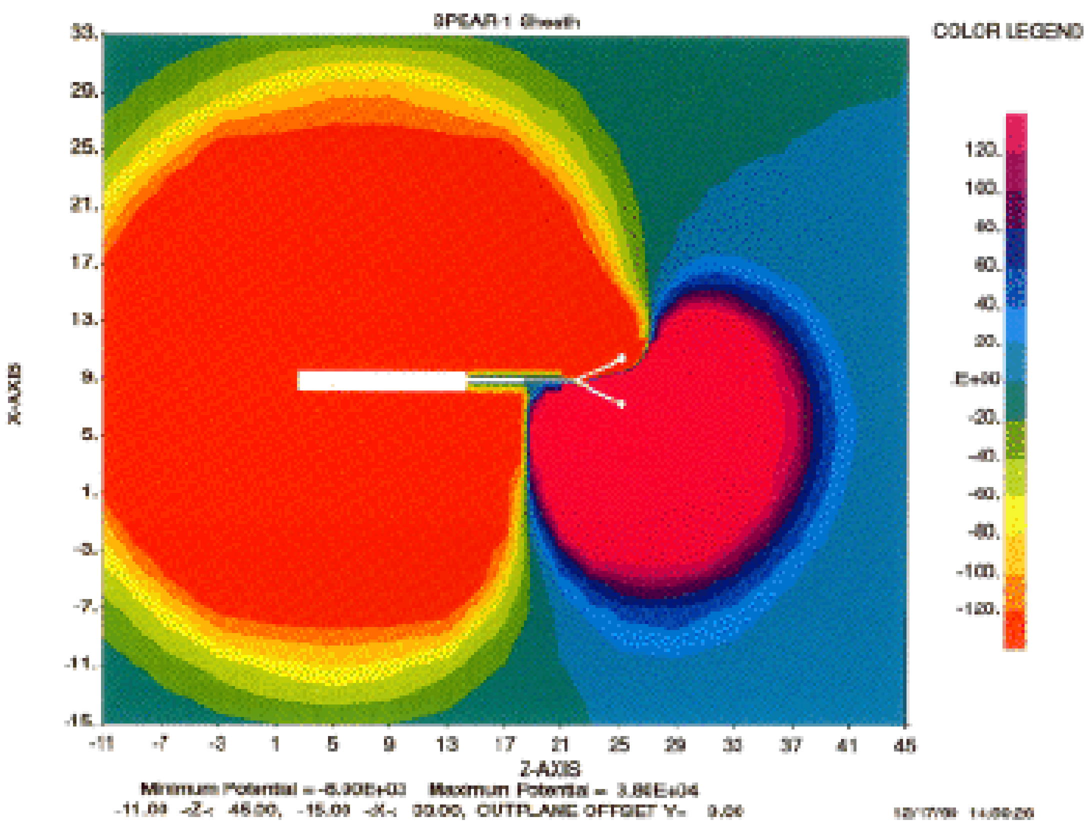
- When charged to a positive potential the distribution can be shifted in energy (in accordance with Liouville's theorem) to provide a corrected data set.



# Potential correction limitations



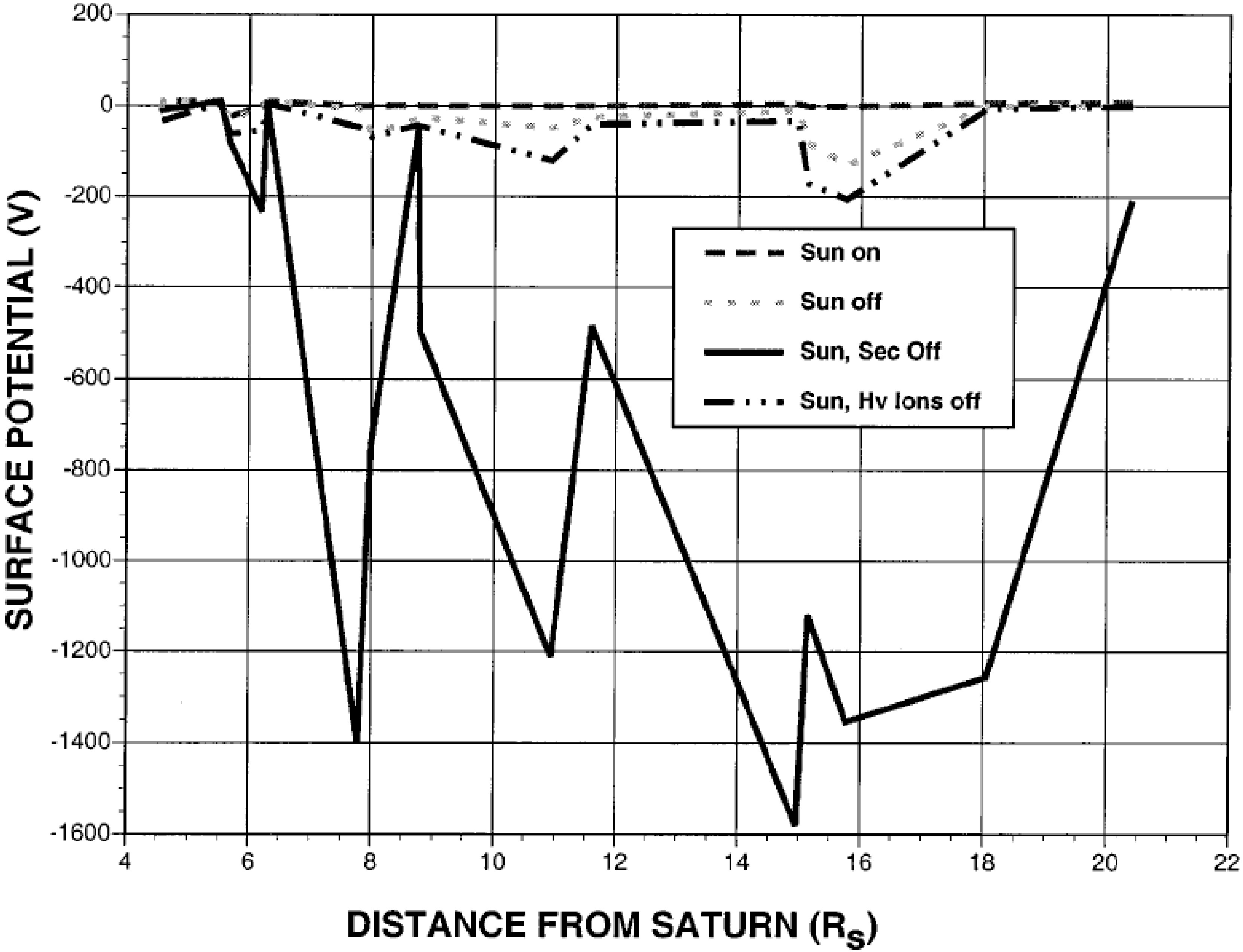
- Measurements (with particle spectrometers) down to a few eV affected by spacecraft potential - uniform potential can be corrected.
- However, large positive potentials can produce density underestimates using this technique - depends on the relative values of $e\Phi_{SC}$ and $k_B T_e$.
- Non-uniform potential must be characterised - low energy bulk velocities and plasma frame anisotropies won't be reliable (e.g., *Scime, Phillips and Bame, 1994*).




*http://ranier.hq.nasa.gov/scrs_page/historic/nascap.html*

# Surface charging validation





# Summary



- Much of the high pressure action is in the hot >10 keV populations there is still a lot of interesting physics and open questions for the cold plasma.

- Variety of species and charge states and strong radial evolution of these populations.

- Challenges due to large dynamic (n: $10^3$-$10^9$ $m^{-3}$) and energy ranges and temporal scales

- Surface charging and particularly surface potential structure could compromise low energy cold plasma measurements <~10 V (direction and under-resolution).

# Backup slides

# Spacecraft charging



Charging currents [c.f., Whipple, 1981]:

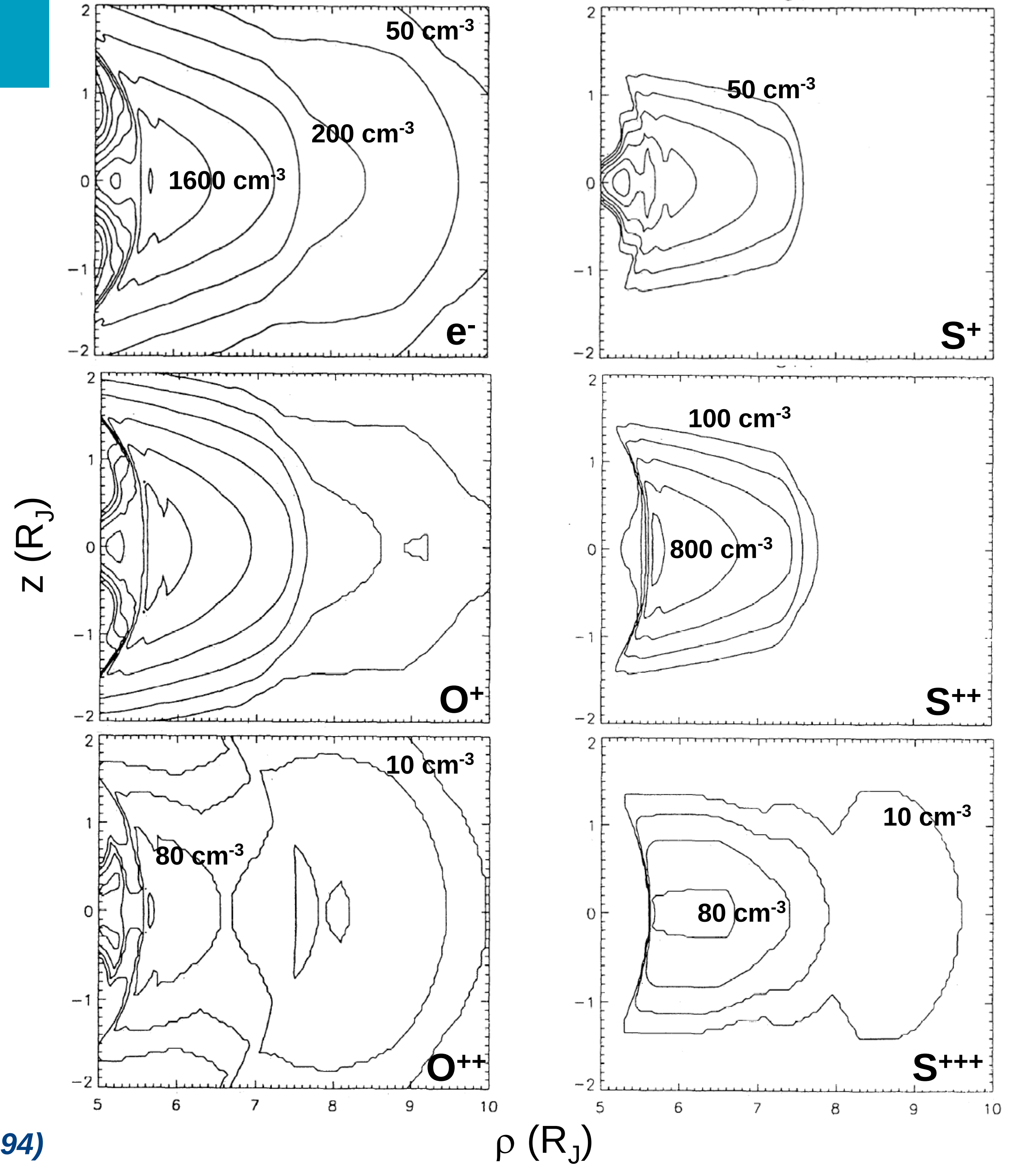
- Thermal electron and ion: $j \sim n(k_B T/m)^{1/2}$
  - Charge positive and negative respectively but generally $k_B T/m$ is much larger for electrons than for ions and so the thermal electron current dominates.
  - This assumes Maxwellian distributions but we know that the distributions are power-laws at high energies.

- Ion ram currents: $j_{ram} \sim nv$
  - Produces negative charging - weak dependence on composition.

- Secondary electron and ion
  - Depend on energy of primaries - region between 6 and 28 keV is largely unexplored - or at best unpublished.

# 2D Maps

- 2D maps from diffusive equilibrium calculations.
- $H^+$ is considered a minor species and is distributed fairly evenly in latitude.
- Contributing 10% to the $e^-$ density at the (cen) equator and 50% at 1.5 $R_J$.




*Bagenal (1994)*

# Non-Maxwellian distributions



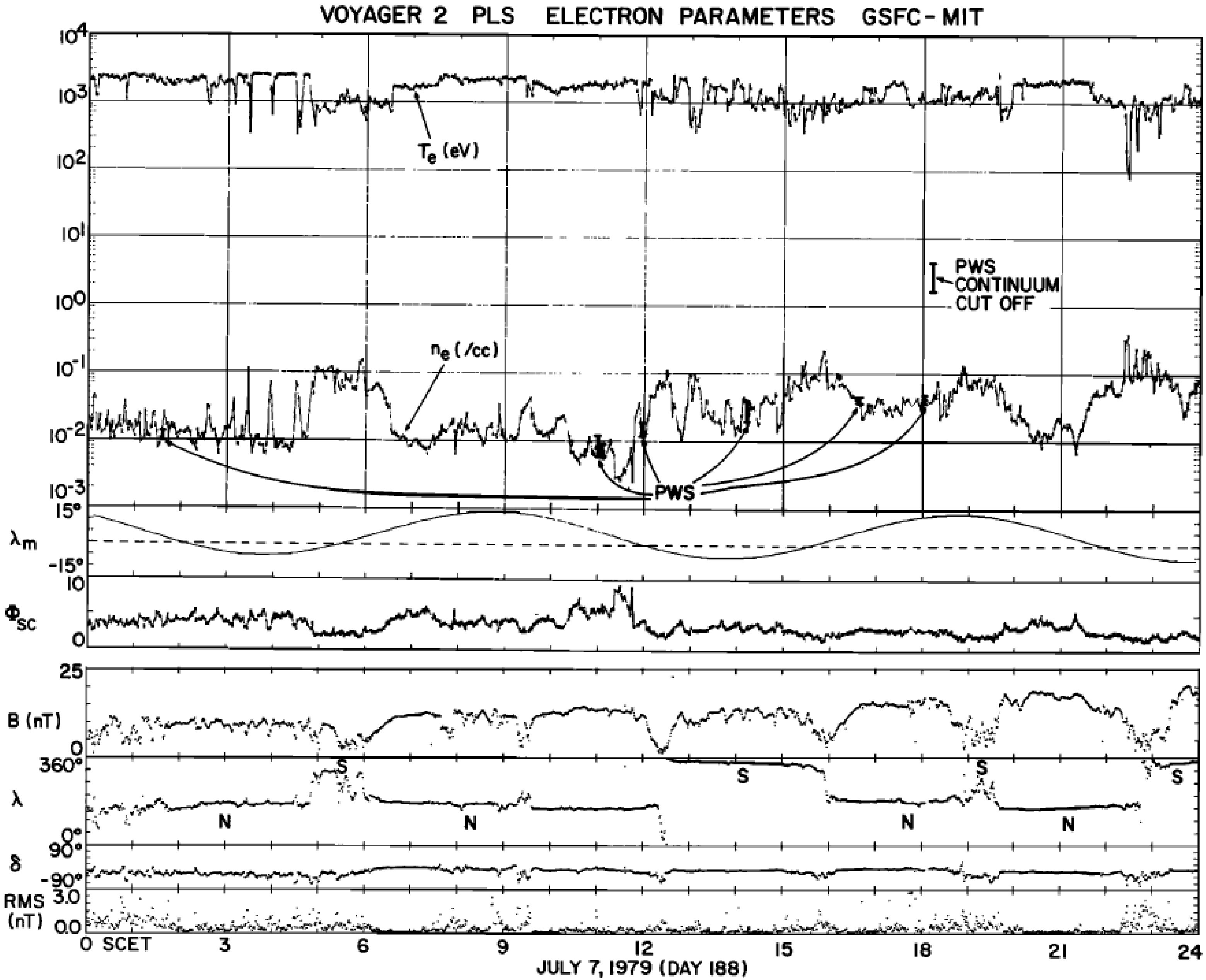
- Turns out that non-Maxwellian electron distributions are important - Ulysses electron observations incompatible with *Bagenal (1994)* model.

- *Moncuquet et al. (2002)* demonstrated that by representing the electron populations using Kappa distributions the observed increase in $T_e$ could be reproduced.

- Changes scale heights and temperature profiles - small changes to density.

- Ion distributions are Maxwellian in the cold torus but not necessarily so in the warm torus.

# Typical $n_e$ and $T_e$




*Scudder, Sittler and Bridge (1981)*