Planetary Magnetospheres: Global Configuration and Dynamics of the Jovian Magnetosphere

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Solar System Seminar S^3

International Max Planck Research School on Processes in the Solar System and Beyond
Max-Planck-Institut für Aeronomie, Katlenburg-Lindau
January 9, 2003

Outline

Introduction

I. Configuration
- inner magnetosphere
- transition inner-middle magnetosphere
- flow pattern
- outer magnetosphere, magnetotail

II. Dynamics
- short-term variations
- long-term variations (>> rotation period)
- boundary phenomena

Future work

The Jovian Magnetosphere

- Dipole axis and rotational axis are tilted by 9.6 degrees
- Io is the main plasma source inside the Jovian magnetosphere
  - Io releases 1 ton of material each second into the magnetosphere
  - Io Torus is formed
- plasma and energetic particles are concentrated in a plasma sheet in the equatorial region of the planet. Particles are sub-corotating with the planet
- centrifugal forces stretch the mass loaded field lines

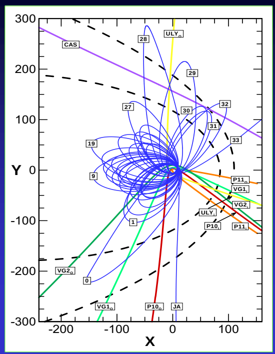
Galileo spacecraft

6.15 m height
4.80 m diameter

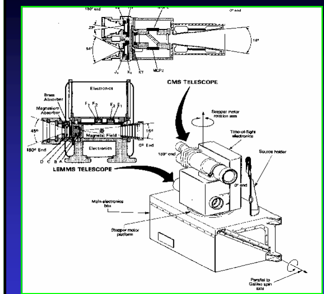
2223 kg mass
- 925 kg fuel
- 339 kg probe

11 scientific experiments
- camera systems
- infrared spectrometer
- ultraviolet spectrometer
- wave spectrometer
- magnetometer
- dust detector
- plasma monitor
- energetic particles detector (EPD)

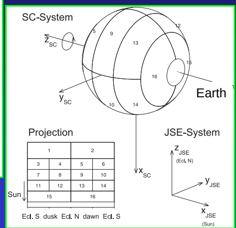
Trajectories of all missions to Jupiter



EPD instrument on Galileo



4π angular coverage
16 sector resolution



Particle motion: Adiabatic invariants

first adiabatic invariant μ :

$$\mu_B = \frac{p_\perp^2}{2m_0B} = const \quad with\ p_\perp = mvsin\alpha$$

α : pitch angle

angle between the direction of the particle and the magnetic field

second adiabatic invariant J :

$$J = 2\int_{x_m}^{x_{m'}} p_\parallel ds = const \quad (or\ \ K = \frac{J}{2\sqrt{m_0\mu_B}})$$

third adiabatic invariant Φ_B :

$$\Phi_B = \oint Bds = constant$$

Phase space density and diffusion

$$f_p = \frac{dN}{dx\,dy\,dz\,dp_x dp_y dp_z} = const$$

z is direction of particle motion

$$dz = v\,dt;\ dx\,dy = dA;\ dp_x dp_y dp_z = p^2 dp d\Omega_s$$

particle flux

$$j = \frac{dN}{dA\,dt\,d\Omega_s v\,dp}$$

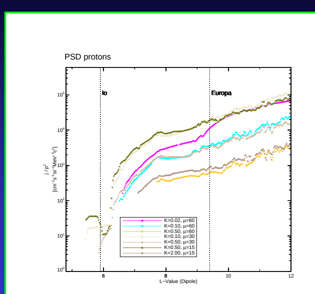
$$f_p = \frac{j}{p^2} = const$$

radial diffusion :

$$\frac{\partial f_p}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{1}{L^2} D_{LL} \frac{\partial f_p}{\partial L}\right) + Q - S \qquad often\ D_{LL} = D_0 L^n$$

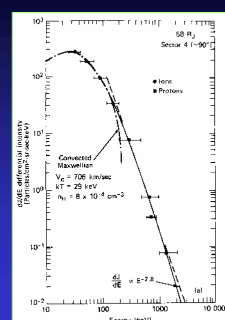
I. 1. Inner Magnetosphere

Phase Space densities 5-12 RJ



- Strong pitch angle diffusion at L=6
- similarities at Io and Europa
- weak D_{LL} dependence of μ and *K*
- diffusion coefficient D_{LL} consistent with power law

Energetic Particle spectra



power law distribution :

$$I = I_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma}$$

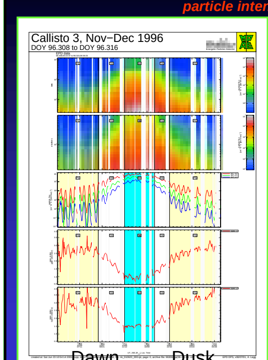
slope γ is called spectral index

hard spectra : γ small

soft spectra : γ large

I. 2. Inner Magnetosphere ⇒ Middle Magnetosphere

particle intensities and spectra

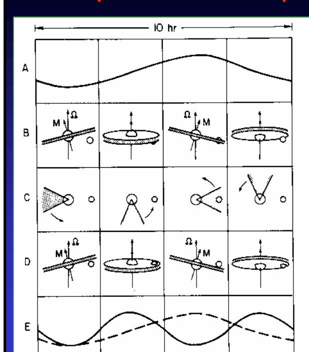


Galileo 1996 (orbit C3)
R= < 40 R_J

Results:

- *particle spectra are harder (small spectral index) in the inner magnetosphere*
- *transition between inner and middle magnetosphere at 15-20 R_J*
- *R > 25 RJ plasma sheet with large 10-h intensity modulations*
- *plasma sheet thickness is asymmetric in local time*

spin modulation in Jupiter's magnetosphere



modulation of particle flux for observer away from magnetic equator or active sector

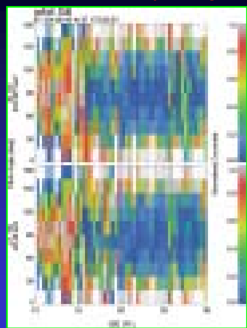
anomaly model
active longitude sector

modulation of particle flux for observer close to magnetic equator

I. 2. Inner Magnetosphere ⇒ Middle Magnetosphere

Electron pitch angle distributions

Pitch angle



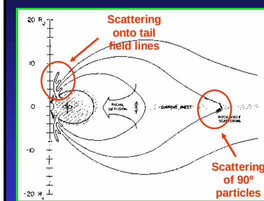
Distance

Galileo 1997 (orbit G8)
R=10-30 R_J

Electrons
304-527 keV
and
29-42 keV

Result:
transition between trapped and bi-directional pitch angle distributions at 10-20 R_J

Model of PAD electron distributions



Sentman et al. 1975
Nishida 1976

Inner Magnetosphere:

- **trapped 'pancake' distributions on dipole-like field lines**

Transition Region / Tail

- **Pitch angle scattering (violation of adiabatic invariants) owing to tail-like field line geometry**
- **current sheet affects electrons with pitch angle of 90° most and at smallest radial distances leading to butterfly/bi-directional field aligned distributions**
- **additional source for field-aligned electrons in the high-latitude ionosphere as a result of non-adiabatic scattering of electrons originally bouncing on dipolar field onto tail field lines (favoured by strong field convergence at high latitudes)**

Corotation in planetary magnetospheres

Neutral atmosphere must corotate with the planet
+
Electrical conductivity Σ must be very large (effective atmosphere/ ionosphere coupling)

$$\vec{I} = \bar{\bar{\Sigma}} \cdot (\vec{E} + \vec{v}_n \times \vec{B})$$
$$\vec{E} = -\vec{v}_{flow} \times \vec{B}$$
$$\Downarrow$$
$$\vec{I} = \bar{\bar{\Sigma}} \cdot (\vec{v}_n - \vec{v}) \times \vec{B}$$

Σ : height-integrated conductivity
v_n : neutral atmosphere velocity
E : horizontal electric field
I : height-integrated current density
v_{flow} : flow velocity above ionosphere

I is coupled by field-aligned currents to the current system in the magnetosphere with current density j

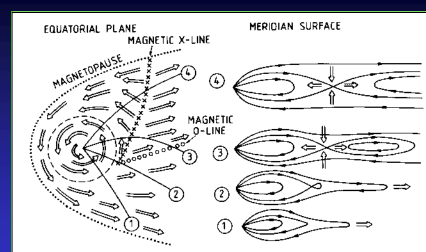
$$\rho \cdot \frac{d\vec{v}}{dt} + \nabla \cdot \bar{\bar{P}} = \vec{j} \times \vec{B}$$

+ radial stress balance

Corotation of plasma

I. 3. Global Flow Pattern

Models of Plasma Flow



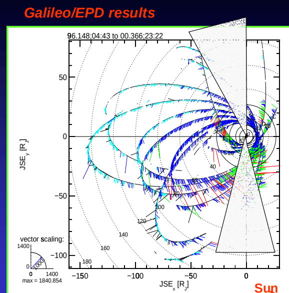
Vasyliunas, 1983

- **plasma flow rotational driven**
- **formation of a magnetic x-line due to internal processes**

I. 3. Measured Global Flow Pattern

Galileo/EPD results

- **flow is predominantly in corotation direction**
- **temporal stable in this averaged view**
- **larger flows with radial outward components (100-200 km/s) at dawn compared to smaller flows with small radial inward components at dusk (50 km/s)**
- **flows in the deep magnetotail still in corotation direction, however substantially subrotational**

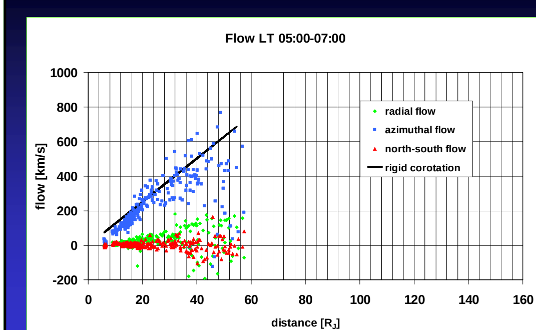


$< 0.2\ v_{rigid}$
$0.2\ v_{rigid} < 0.8\ v_{rigid}$
$0.8\ v_{rigid} < 1.2\ v_{rigid}$
$> 1.2\ v_{rigid}$

Krupp et al., 2001

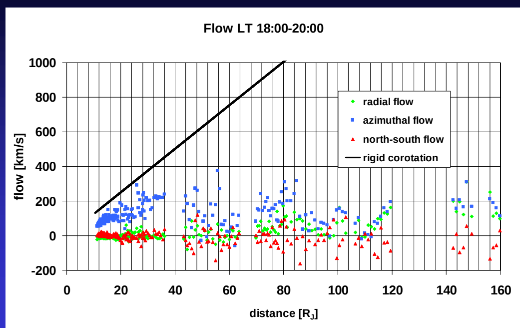
I. 3. Plasma Flow Pattern

strong local time asymmetry



I. 3. Plasma Flow Pattern

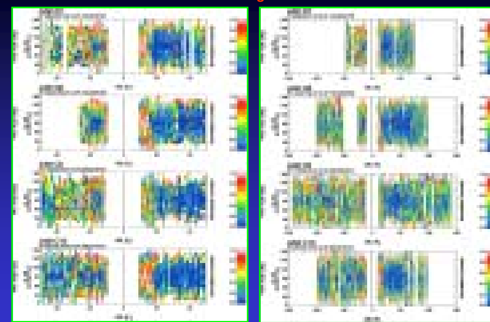
strong local time asymmetry



I. 4. Outer Magnetosphere and Magnetotail

Electron Pitch angle distributions

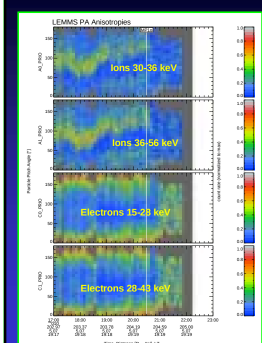
Pitch angle



R < 50 R_J Distance R < 150 R_J

I. 4. Outer Magnetosphere

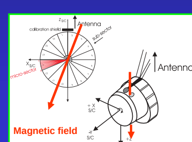
Pitch angle distributions in the Dusk Jovian magnetosphere



CASSINI in the Jovian magnetosphere 2001.010 at 204 R_J

- **Ions are convected nearly perpendicular to the magnetic field direction**
- **Electrons are bi-directional along the magnetic field**

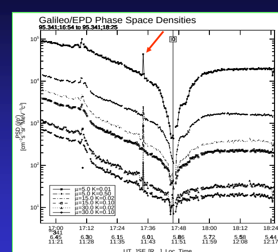
Result:
Closed magnetic field topology at 200 R_J in the dusk side magnetosphere



II. 1. Short-Term Variations

Interchange events in the inner magnetosphere

phase space density f



Distance R

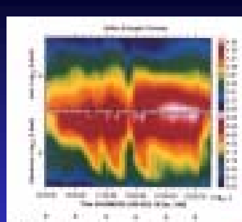
Change in phase space density of energetic particles at constant μ and K values is nice indicator for interchange events

associated with changes in magnetic field and wave emissions

II. 1. Short-Term Variations

Injection events in the inner magnetosphere

Energy
electrons ions



Distance R

Dispersive injection events

•occur at all local times 9-27 RJ
•radial displacement of > 1 RJ

Mauk et al., 1997

Particle drifts

$$\vec{v}_D = \frac{\vec{B}\times\nabla\Phi_{eff}}{B^2}$$

$$\Phi_{eff} = \Phi_{conv} + \Phi_{cor} + \Phi_{\nabla B}$$

$$\Phi_{conv} = -E_0 r\sin\varphi \propto r$$

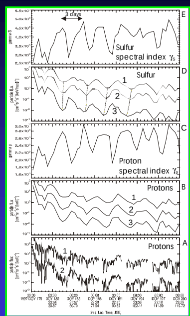
$$\Phi_{cor} = \frac{\omega_{rot}B_0R^3}{r} \propto \frac{1}{r}$$

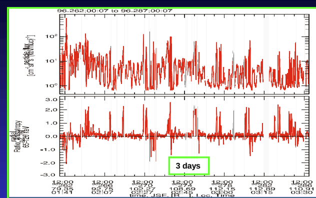
$$\Phi_{\nabla B} = \frac{\mu_B B_0 R^3}{q r^3}$$

B_0 : surface magnetic field at the equator
R : planet's radius
r : distance of the particle from the center of the planet
E_0 : dawn-to-dusk electric field

II. 2. Long-Term Variations

Variations in intensities and spectral slopes





Woch et al., 1998

- 2.5-3 day modulation of energetic particle intensities, radial anisotropies and spectral indices in the Jovian magnetotail
- 4-5 day modulations in plasma (Vasyliunas et al.)

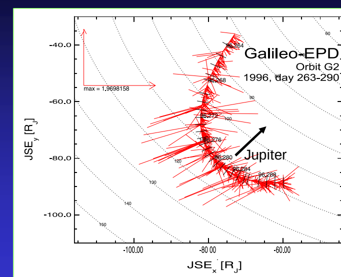
II. 2. Long-Term Variations

Particle flow bursts

Ion bursts in the distant tail

- field-aligned / radial outward (inward)
- periodicity of 2.6+/-0.4 days

(Krupp et al., GRL, 1998)

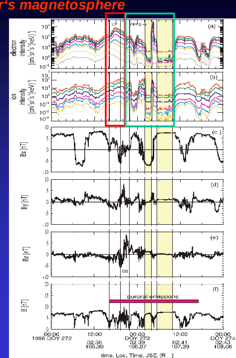


II. 2. Long-Term Variations

Substorm scenario in Jupiter's magnetosphere

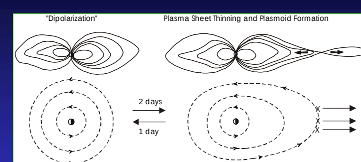
- "plasma loading phase"
  ⇒ increase of particle intensities at low energies
  ⇒ onset of auroral emissions
  ⇒ distortions in magnetic field
- bipolar signature in B_Z with strong "core" field (B_Y); plasmoid with flux rope structure
- thinning of current sheet / plasma sheet - excursions far into lobe
  ⇒ drop in cut-off frequency of the continuum (low plasma density)
  ⇒ low fluctuation level in magnetic field
  ⇒ particle intensities at background
  ⇒ particle beams at lobe / plasma sheet interfaces
- scenario takes several planetary rotations to develop

⇒process of global nature



II. 2. Long-Term Variations

Variations in intensities and flow bursts



⇒ tentatively suggests that processes are internally driven

mass loading with characteristic, intrinsic time constant

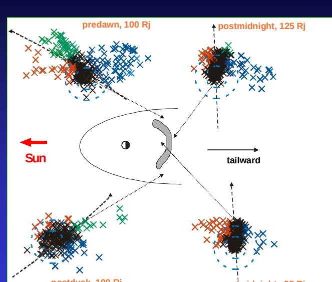
II. Long-Term Variations

Particle Flow bursts - Statistics

Based on ~ 12,000 anisotropy measurements (30-min averages, binned and normalized with respect to the average anisotropy)

- large number of events with increased anisotropy/flow (compared to the average anistropy) and significant directional deviation in the tail
- events scatter around the antisunward/sunward direction (radial inward/outward direction)
- inward directed bursts dominate closer to the planet, outward directed bursts at larger distances

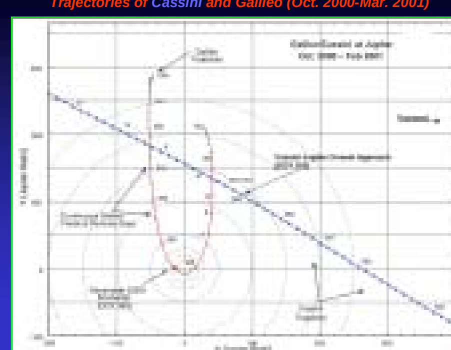
x-line at
pre-dawn: 70 RJ
pre-midnight: 120 RJ

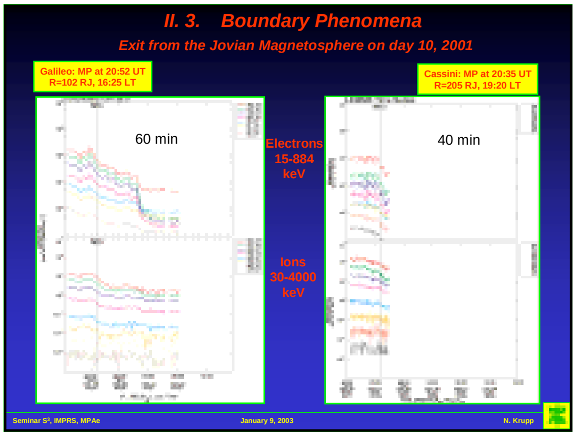


Characteristic distributions

II. 3. Boundary Phenomena

Trajectories of Cassini and Galileo (Oct. 2000-Mar. 2001)




II. 3. Boundary Phenomena
Exit from the Jovian Magnetosphere on day 10, 2001
Galileo: MP at 20:52 UT
R=102 RJ, 16:25 LT
Cassini: MP at 20:35 UT
R=205 RJ, 19:20 LT
60 min
40 min
Electrons
15-884
keV
Ions
30-4000
keV
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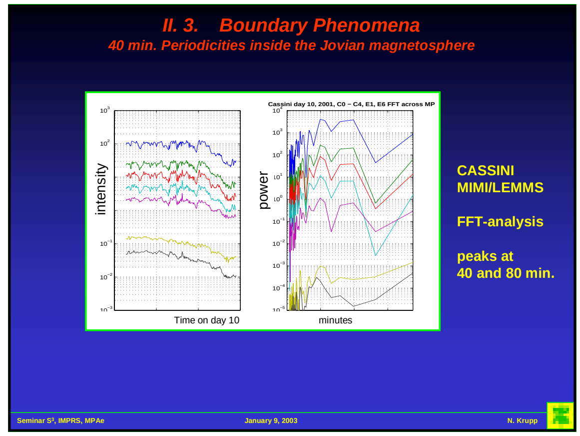
II. 3. Boundary Phenomena
40 min. Periodicities inside the Jovian magnetosphere
Cassini day 10, 2001, C0 – C4, E1, E6 FFT across MP
intensity
power
Time on day 10
minutes
CASSINI
MIMI/LEMMS
FFT-analysis
peaks at
40 and 80 min.
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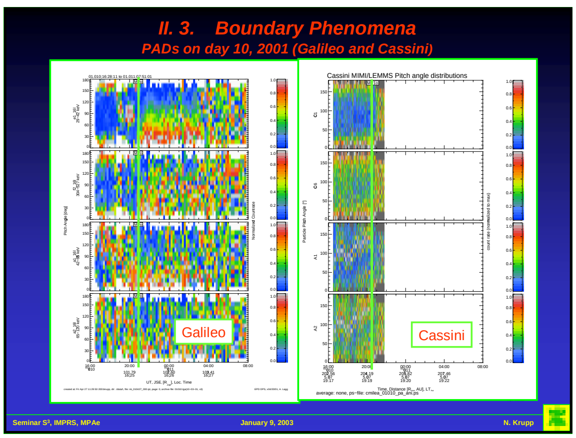
II. 3. Boundary Phenomena
PADs on day 10, 2001 (Galileo and Cassini)
Cassini MIMI/LEMMS Pitch angle distributions
Galileo
Cassini
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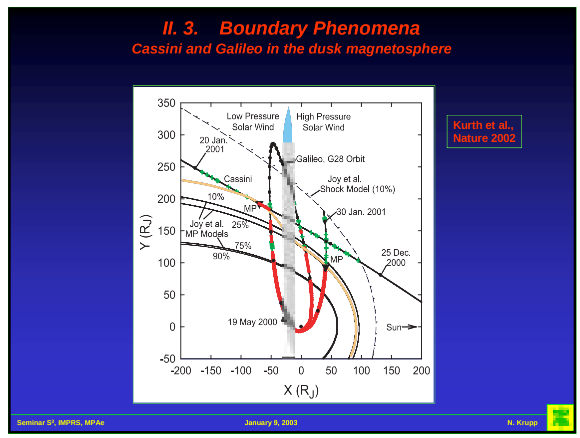
II. 3. Boundary Phenomena
Cassini and Galileo in the dusk magnetosphere
Low Pressure
Solar Wind
High Pressure
Solar Wind
20 Jan. 2001
Galileo, G28 Orbit
Cassini
Joy et al.
Shock Model (10%)
10%
MP
30 Jan. 2001
Joy et al. 25%
MP Models
75%
90%
MP
25 Dec. 2000
19 May 2000
Sun
Y (RJ)
X (RJ)
Kurth et al.,
Nature 2002
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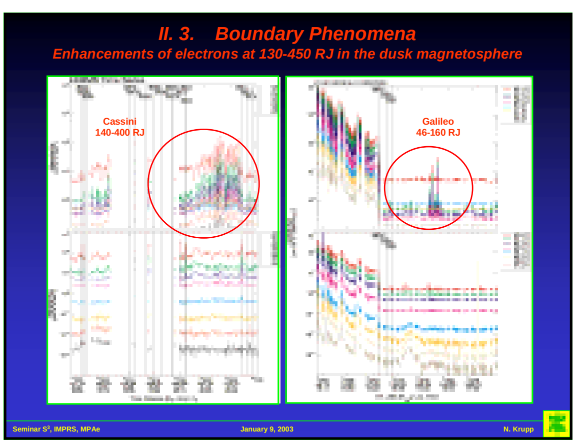
II. 3. Boundary Phenomena
Enhancements of electrons at 130-450 RJ in the dusk magnetosphere
Cassini
140-400 RJ
Galileo
46-160 RJ
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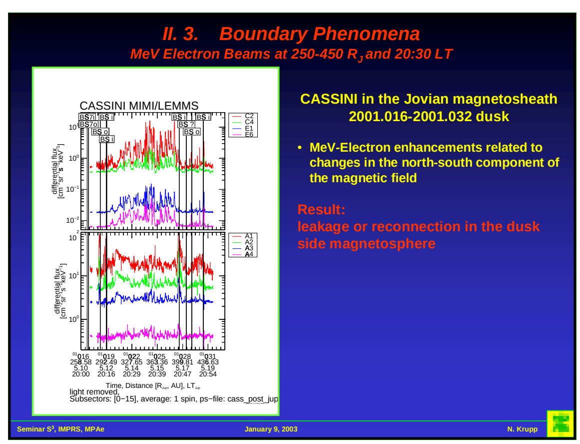
II. 3. Boundary Phenomena
MeV Electron Beams at 250-450 RJ and 20:30 LT
CASSINI MIMI/LEMMS
CASSINI in the Jovian magnetosheath
2001.016-2001.032 dusk
• MeV-Electron enhancements related to changes in the north-south component of the magnetic field
Result:
leakage or reconnection in the dusk side magnetosphere
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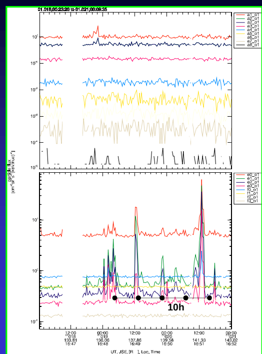
II. 3. Boundary Phenomena

Electron Beams at 135-140 R_J and 16:50 LT

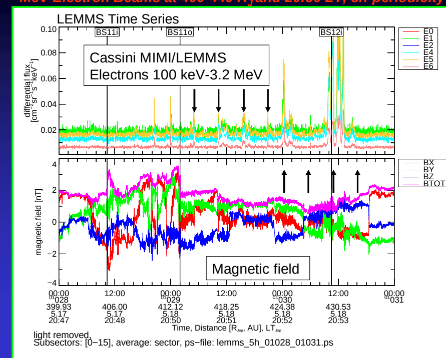


Galileo/EPD
days 18-21, 2001

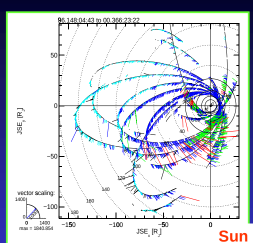
- Electron upstream events at energies between 15 and 884 keV
- 10h-periodicity
- nearly no signature in ions

II. 3. Boundary Phenomena

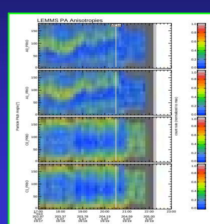
MeV Electron Beams at 400-440 R_J and 20:50 LT; 5h-periodicity



Configuration Summary

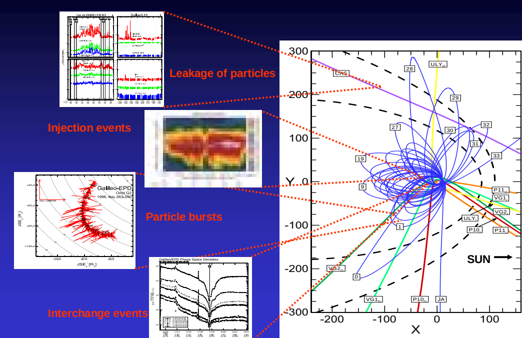


Bi-directional electron distributions
Closed magnetic field configuration out to 200 RJ



Global flow pattern
with dawn-dusk asymmetry
sub-corotational flow

Dynamics Summary



Open questions

- What are the source processes for Jupiter's aurora?
- What is the solar wind influence on the Jovian magnetospheric dynamics?
- What is triggering the substorm-like events in the Jovian magnetosphere?
- Transport and Acceleration of the Jovian plasma?

Conclusions

Configuration

- Galileo and Cassini enhanced the understanding of the global configuration of the Jovian magnetosphere dramatically
- Between 15 and 20 RJ the particle configuration changes significantly
- Analysis of first-order anisotropies in particle distributions reveal a strong local time asymmetry between dawn and dusk at distances R= 25-40 RJ
- The global flow pattern is corotation dominated
- Bi-directional electron pitch angle distributions indicate a possible closed magnetic field configuration in the Jovian magnetosphere from 25 RJ to the MP

Conclusions

Dynamics

- **Variations of particle intensities and spectra on long and short-term time scales ⇒ substorm-like processes, instabilities**
- **boundary phenomena ⇒ reconnection, leakage, upstream events**
- **The rotational driven particle flow is frequently disrupted by particle flow bursts**
- **They occur predominantly in the pre-midnight to pre-dawn sector of the distant tail (beyond ~50 Rj)**
- **The bursts are part of global processes with analogies to terrestrial substorms**
- **They are possibly initiated at an x-line located between 70 to 120 Rj (inferred from the predominance of inward or outward bursts)**
- **Unclear whether processes are internally or solar wind driven, however we tentatively favor an internal process (mass loading of flux tubes from internal sources rather than solar wind energy storage)**