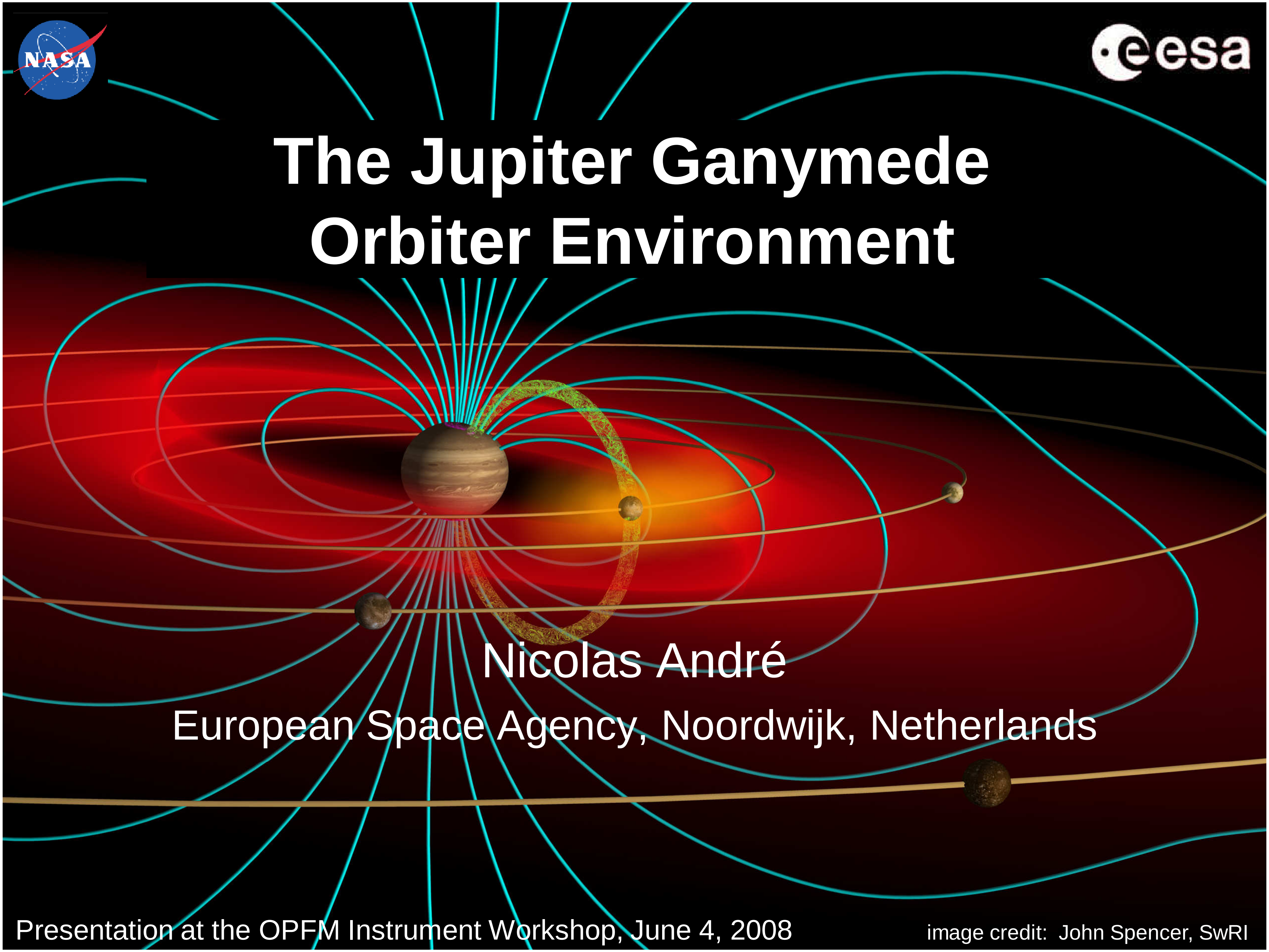
# The Jupiter Ganymede Orbiter Environment



Nicolas André

European Space Agency, Noordwijk, Netherlands

Presentation at the OPFM Instrument Workshop, June 4, 2008

image credit: John Spencer, SwRI

# Outline

I. Missions to Jupiter:
Radiation Working Group and Radiation Models Available at ESA

II. Jupiter Ganymede Orbiter:
Mission Analysis and Radiation Doses

III. In Orbit Around Ganymede:
The Local Radiation Environment of Ganymede

IV. Future Steps

# I. Missions to Jupiter: Radiation Working Group and Radiation Models Available at ESA

# I1. Introduction

A major design factor that makes missions to Jupiter and its moons difficult is the intense radiation belts that exist at Jupiter.

These radiation belts have been modelled empirically and physically by various groups in Europe and in the United States.

The end results are used to constrain potential mission scenarios and estimate the total radiation dose.

It is therefore critical to have a good and robust understanding of the radiation environment of Jupiter.

=> external Radiation Working Group set up at ESA

# I2. Objectives of the Radiation Working Group

a) Critically review existing radiation environment models

b) Study the differences between models available in Europe and US

c) Evaluate the efforts needed to consolidate the current models

d) Ensure the availability of a consolidated model that shall be used for the remainder of the study, the ESA CDF studies, as well as the other working groups (in strong synergy)

e) Recommend and coordinate new ground-based observations

# I3. Members of the Radiation Working Group

Nicolas André (ESA)
John Sorensen (ESA)
Arno Wielders (ESA)
Sébastien Bourdarie (ONERA)
Michele Dougherty (IC)
Norbert Krupp (MPS)
Joachim Saur (Cologne University)
Helmut Rucker (IWF)
Philippe Zarka (Meudon)

\+ US colleagues
Insoo Jun (JPL)
Hank Garrett (JPL)

\+ Japanese colleagues
Takeshi Takashima (JAXA)
Hiroaki Misawa (Tohoku University)
Yoshizumi Miyoshi (Nagoya University)

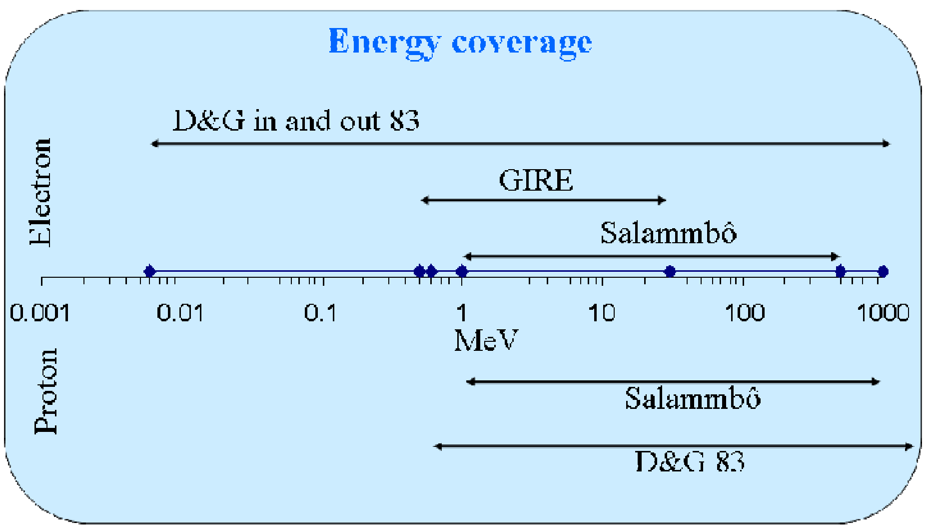
\+ Russian colleague
Mikhail Podzolko (IKI)

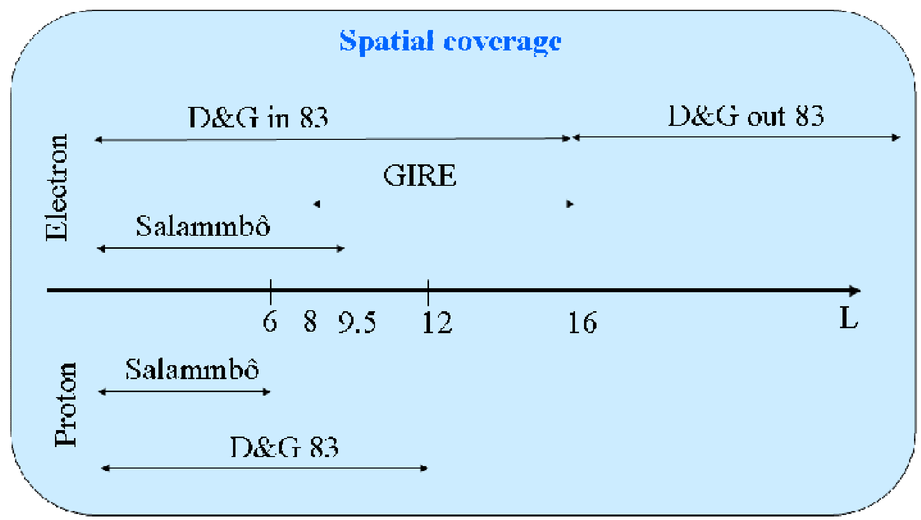
# I4. Radiation Models Currently Available

Jovian radiation belts (electron, protons) have been modelled empirically (D&G, GIRE) and physically (Salammbô) by various groups in the United States (JPL, SwRI) and in Europe (ONERA):

a) different approaches
b) different input parameters (e.g., magnetic field models)
c) different spatial coverage
d) different energy coverage

Courtesy of Sébastien Bourdarie



# I5. ESA Approach

Philosophy:

Take advantage of all these pre-existing models by combining them together and then get the best specification we could obtain at the present time for any spacecraft which will fly in the Jovian magnetosphere

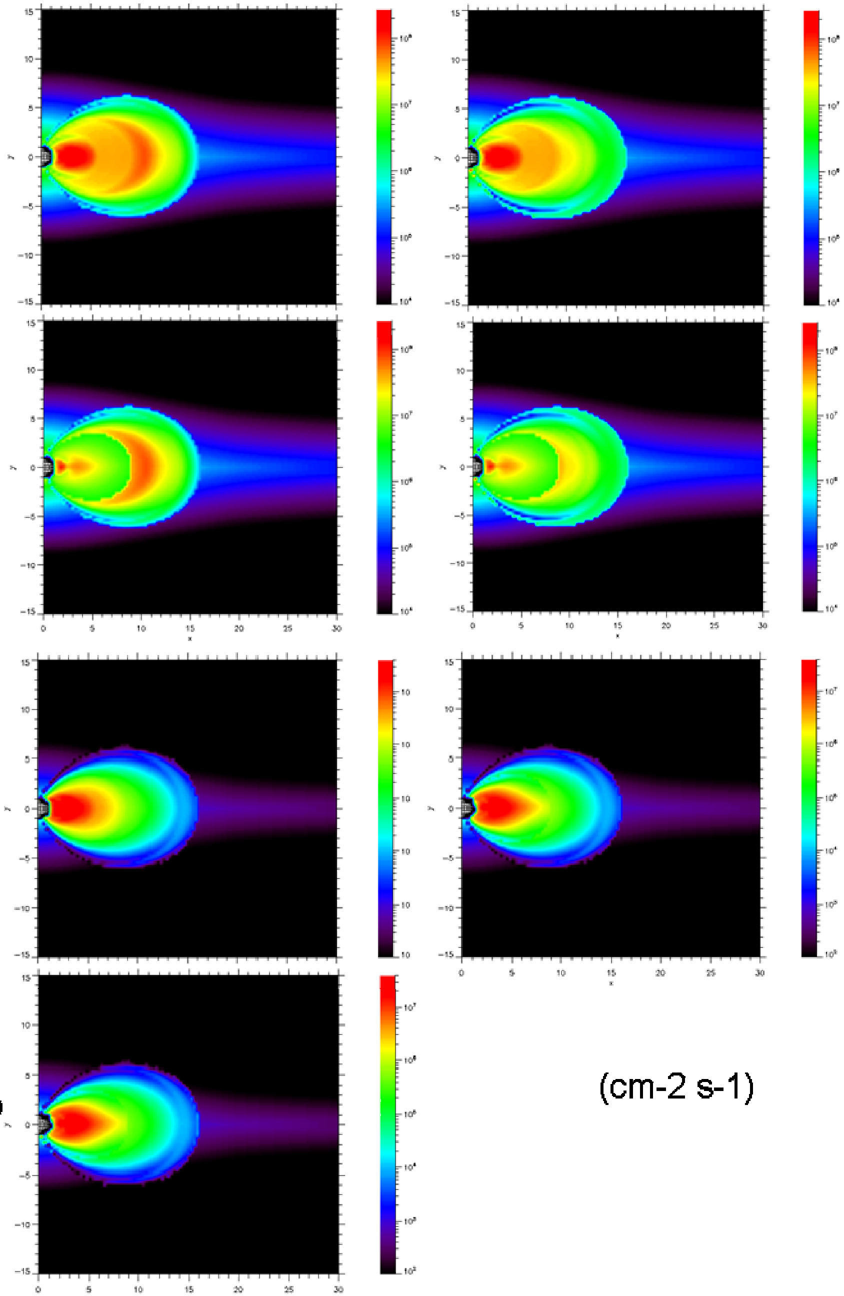
In practice: (e.g., electron model)

The model currently available at ESA allows to combine D&G83, plus GIRE plus Salammbô. The selection from one model to the other is done first according to L and then according to the energy.

=> JOP/JOE model provided by ONERA

# I6. JOP/JOE Model

Omni-directional integral electron flux



DG83

DG83 GIRE

DG83 Salammbô

DG83 Salammbô GIRE

E>1 MeV, L=[0:30]
Small discontinuities

DG83

DG83 Salammbô

E>20 MeV, L=[0:30]
Stretched field effects

DG83 Salammbô GIRE

(cm-2 s-1)

# II. Jupiter Ganymede Orbiter:
# Mission Analysis and Radiation Doses

# Jupiter Ganymede Orbiter

The Europa Jupiter System Mission (EJSM) is an international mission proposed to be developed in collaboration between NASA, ESA, and JAXA.

Reference mission architecture:

A Jupiter Europa Orbiter (JEO), NASA
A Jupiter Ganymede Orbiter (JGO), ESA
A Jupiter Magnetospheric Orbiter (JMO), JAXA

with possibly a Europa Lander (Roscosmos) as a stand-alone mission

JEO will focus on the two 'rocky' inner Galilean satellites, Io and Europa.

JGO will focus on the two 'icy' outer Galilean satellites, Ganymede and Callisto.

# II1. JGO: CDF Study (on-going)

Launch: March 2018

Arrival at Jupiter: October 2024

Ganymede GA before JOI

JOI injects the S/C into a 25:1 resonant orbit with Ganymede
Orbit period reduction with Ganymede

Tour including Ganymede (6x) and Callisto (2x) GA to transfer to Callisto

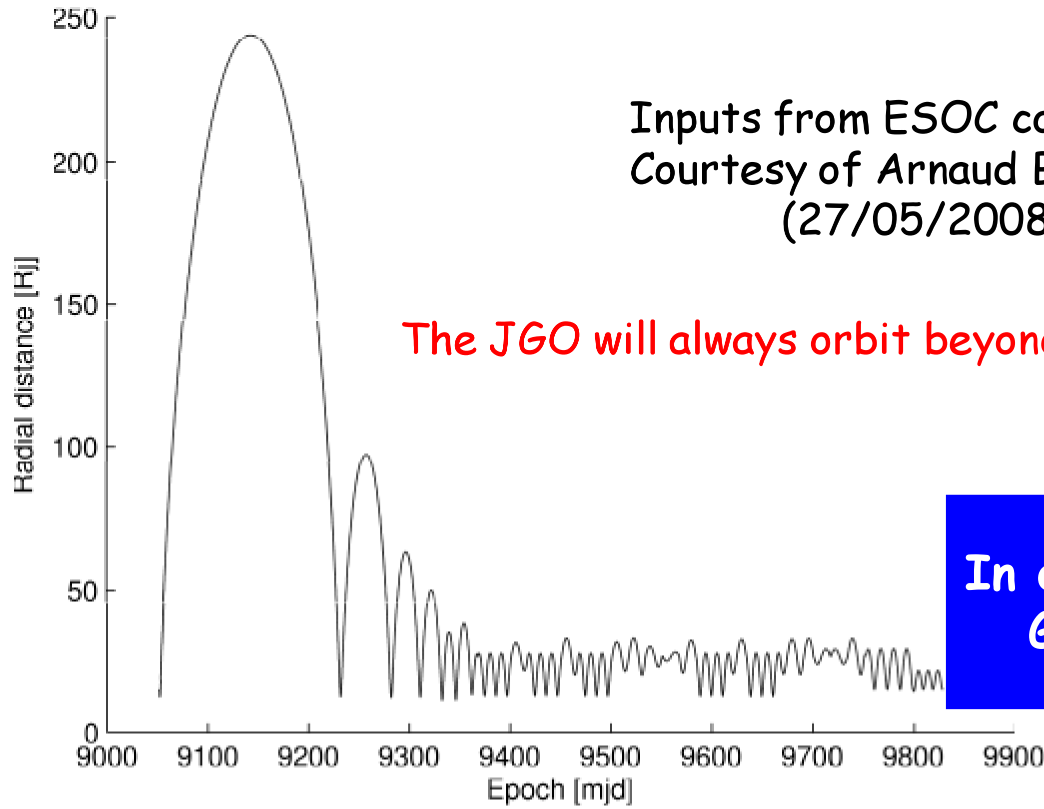
Pseudo-orbiter around Callisto

Tour including Ganymede (2x) and Callisto (1x) GA to transfer to Ganymede

Injection into an elliptical orbit around Ganymede to analyze the magnetosphere (e.g. 200x4000 km)

Circularisation around Ganymede
Full moon coverage is performed from low altitude (200 km) near polar orbit

# II2. JGO: Mission Analysis




Inputs from ESOC colleagues
Courtesy of Arnaud Boutonnet
(27/05/2008)

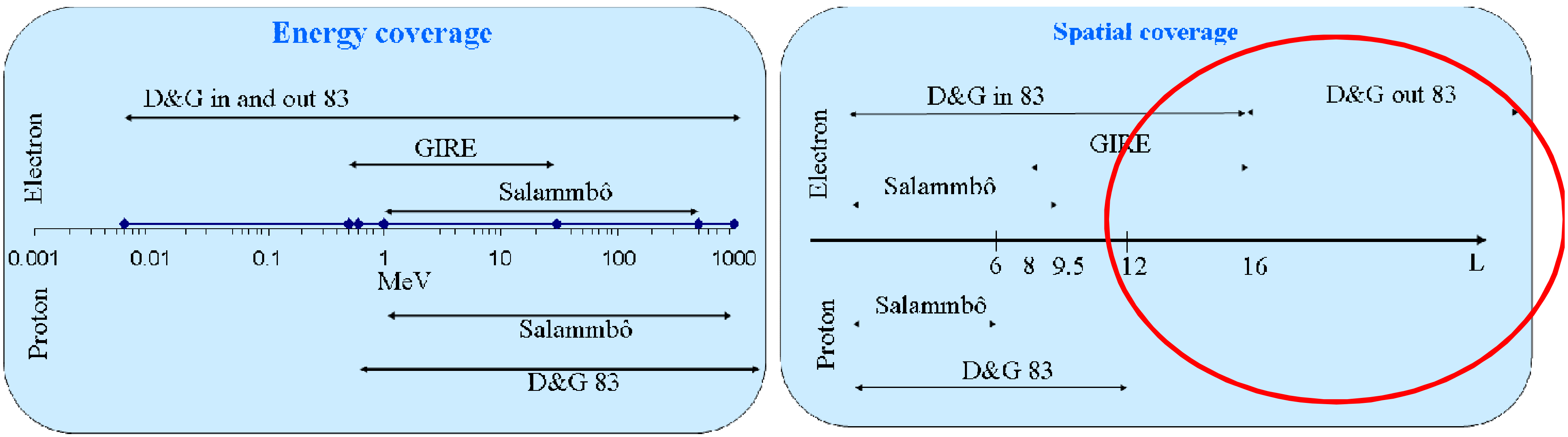
The JGO will always orbit beyond ~12 Rj

**In orbit around Ganymede**

Mission requirement: total radiation dose below 100 krad

# II3. Implication for the design of the JGO

Courtesy of Sébastien Bourdarie



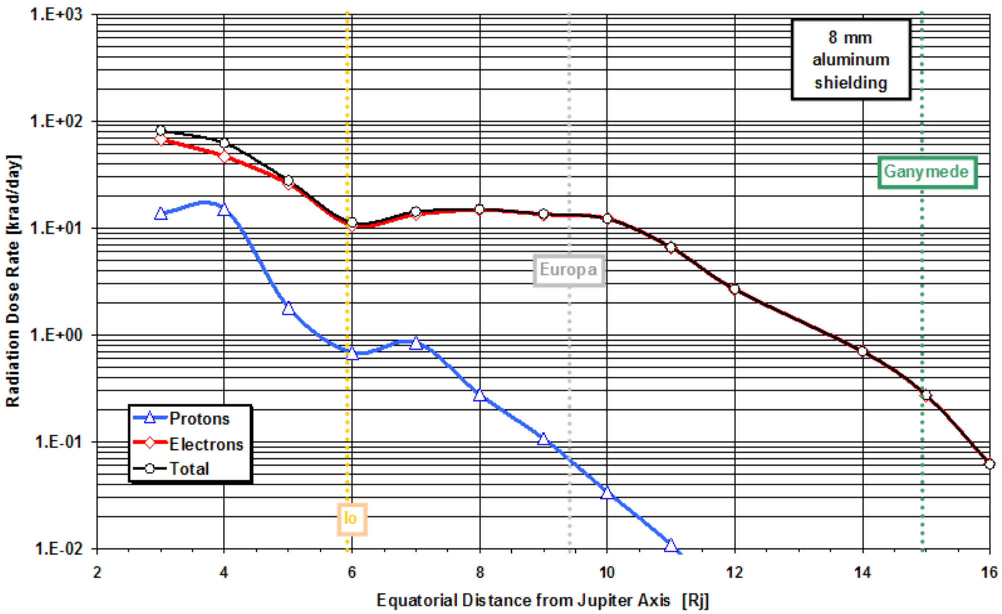

The JGO will always orbit beyond ~12 Rj

=> use of the GIRE or D&G models

# II4. Implication for the design of the JGO

Courtesy of John Sorensen

Mission Analysis:
Use of the D&G model




Radiation dose as a function of the distance to Jupiter for several Al thicknesses using the ONERA-full model (D&G + GIRE + Salammbô) compared with D&G only

This approach is conservative since the D&G model gives the highest radiation dose

Beyond 16 Rj the radiation doses drop significantly

Implication: the radiation doses within 16 Rj are the most constraining ones

# II5. Implication for the design of the JGO

Mission Analysis:
Use of the D&G model

The GIRE model is a statistical model,
including average and standard deviations

The D&G model is ~ included
in the statistical GIRE model
(~ + 1σ standard deviation)

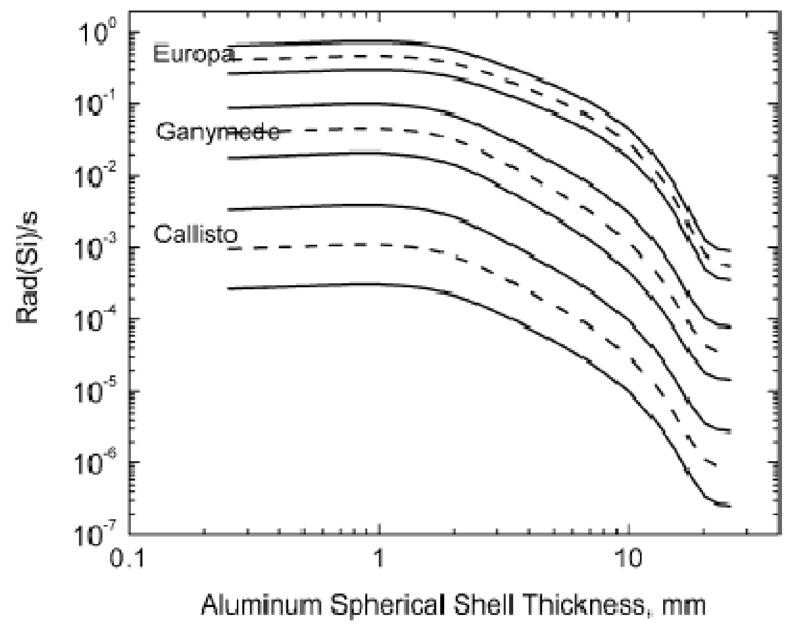



Fig. 8. Dose–depth curves for an aluminum spherical shell configuration using the fluxes given by Eqs. (6)–(8). Three dose–depth curves are shown for each moon. The dashed lines in the middle are the average doses, and the upper and lower curves are the upper and lower limits for a 1σ standard deviation. The NOVICE radiation transport code (Jordan, 2000) was used for these calculations.

Jun et al., Icarus, 2005

# II6. JGO: Total Radiation Doses

Mission Analysis:

The most constraining phase in term of radiation doses is the phase when the JGO orbits around Ganymede

elliptical orbit (200x4000 km): 80 days
circular orbit (200x200 km): 180 days

~ 100 krad / year behind 8 mm Al shielding

# II7. Implication for the design of the JGO

Mission Analysis:

- The most constraining phase in term of radiation doses is the phase when the JGO orbits around Ganymede

- Radiation doses behind 8 mm Al shielding to keep them below 100 krad

Decreasing the shielding thickness from 8 mm to 4 mm would result in an increase of a factor 3 in term of radiation dose at Ganymede's location

=> More limited lifetime

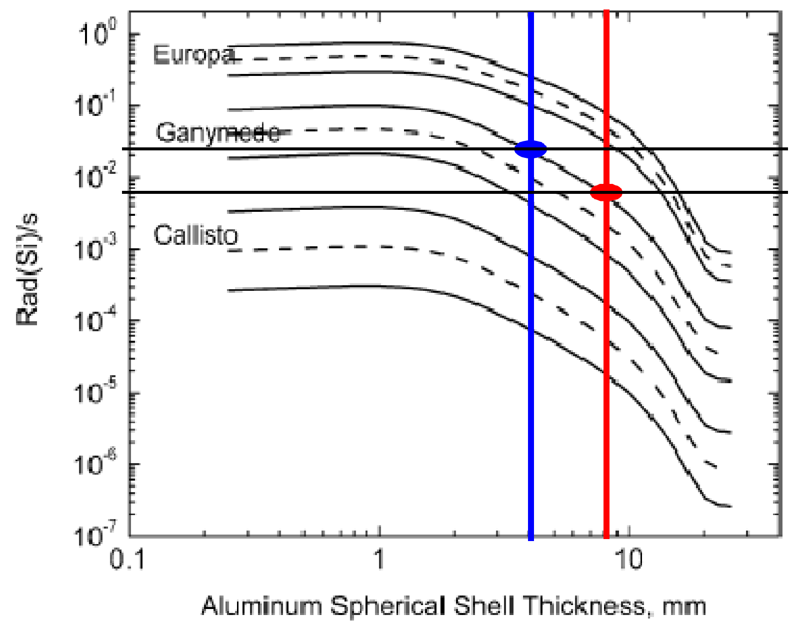



Fig. 8. Dose–depth curves for an aluminum spherical shell configuration using the fluxes given by Eqs. (6)–(8). Three dose–depth curves are shown for each moon. The dashed lines in the middle are the average doses, and the upper and lower curves are the upper and lower limits for a $1\sigma$ standard deviation. The NOVICE radiation transport code (Jordan, 2000) was used for these calculations.

Jun et al., Icarus, 2005

# II8. Implication for the design of the JGO

But, designing a mission in orbit around Ganymede
needs to take into account
the local radiation environment of the moon,
in particular the shielding effects
from Ganymede's intrinsic magnetic field

However, so far, we are designing (in term of radiation doses)
a mission that would orbit at Ganymede's location
but NOT around Ganymede itself !

# II9. Remember the Case of Europa

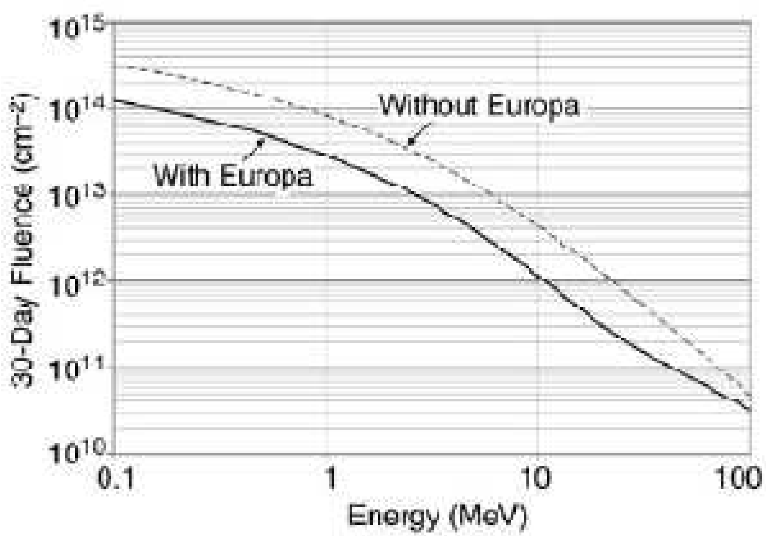



Figure 2. Calculation of 30-day electron fluence, or number of particles per cm² above a cutoff energy. The upper curve shows the fluence when Europa is absent and the lower curve shows the fluence when an approximate reduction is made, using the parameters of Table 1.

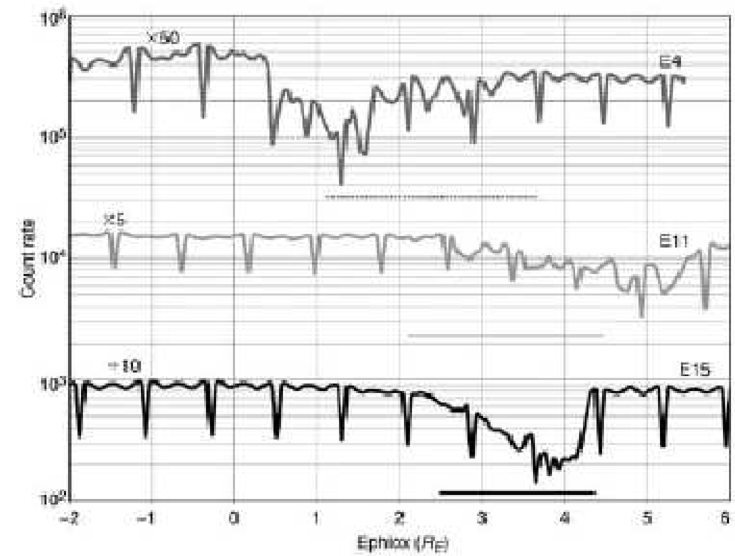



Figure 3. Spin-averaged count rates from the ~1.5–10.5 MeV electron channel on EPD plotted as a function of ephiox, the x-axis of the ephio system. The horizontal lines correspond to the nominal geometric wakes in ephio coordinates.

In the case of Europa, Paranicas et al., GRL, 2007 took into account charged particle motions in the vicinity of the moon and, taking into account obscuration effects, have shown that the radiation doses are reduced by a factor of ~3 when orbiting around Europa, compared to being in orbit at Europa's location (NASA Europa Explorer Flagship study)

III. In Orbit Around Ganymede:

The Local Radiation Environment Of Ganymede

# III1. Solar System Magnetospheres

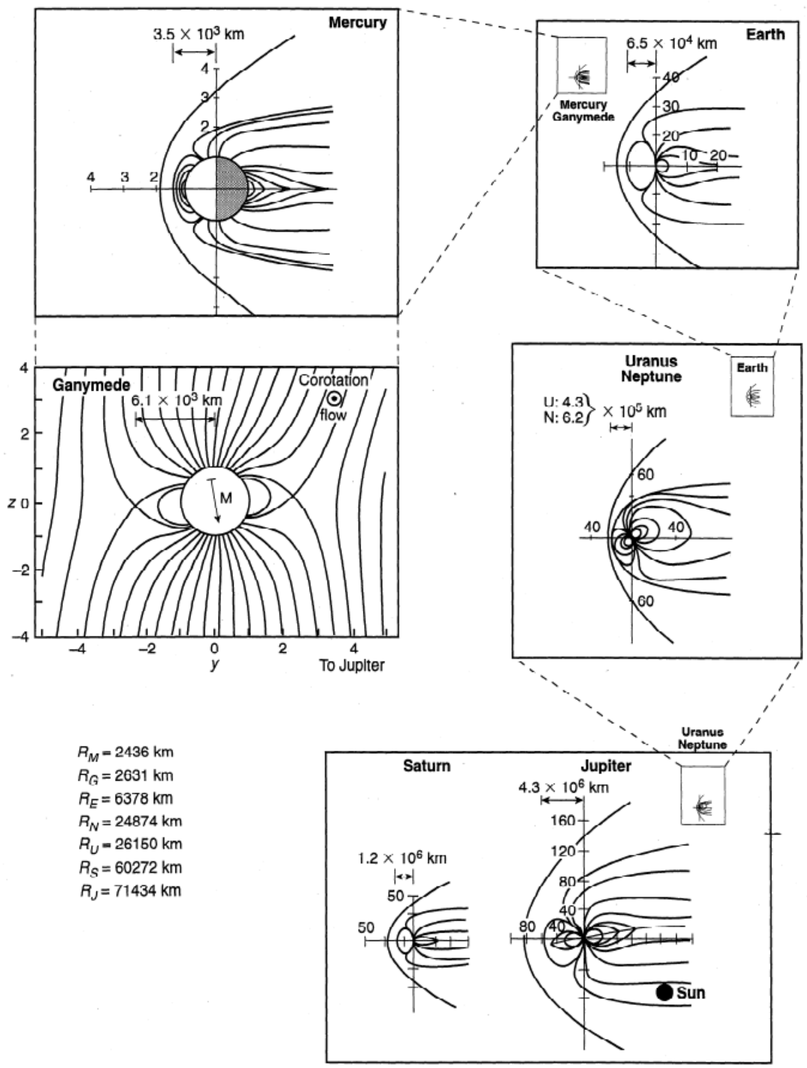



**Figure 7.** Schematic showing the known solar system magnetospheres. The axes are scaled in units of the radius of the body, given in the lower left for each body.

# III2. Ganymede's Magnetosphere: Basic Facts

**Ganymede's orbit:**

- 14.97 Rj (1 Rj = 71492 km)

**A unique example of an internally magnetized moon:**

- Centered dipole whose north pole is tilted 4° from the spin axis toward 336° Ganymede west longitude
- Equatorial field surface strength: 719 nT
- Northward-oriented dipole

**Ganymede's mini-magnetosphere:**

- Roughly 2 Rg (1 Rg=2631 km)
- Transverse scale of the magnetosphere ~5.5 Rg
- Ganymede's distant wake extends ~ 30 Rg ?

**Importance of Reconnection**

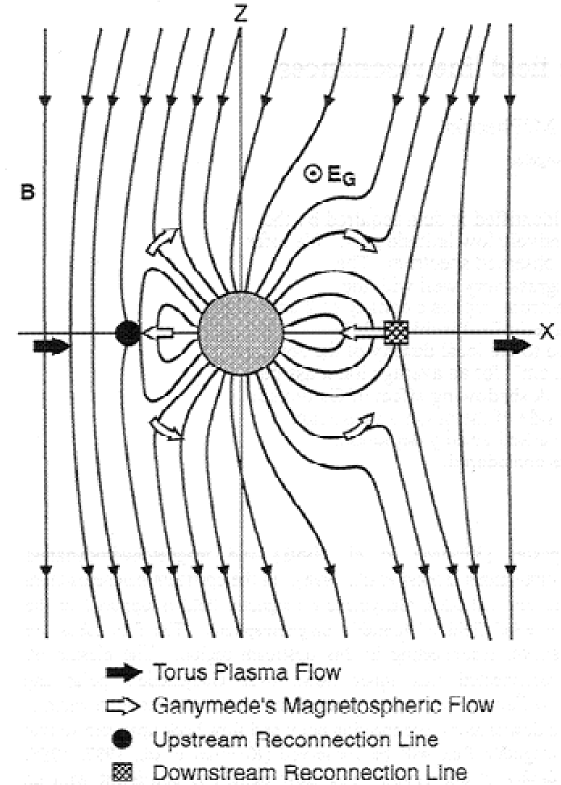



**Figure 1.** Schematic view from outside of Ganymede's magnetosphere looking toward Jupiter. This is a plane through Ganymede's spin axis (Z) that contains the vector along the direction of torus plasma flow. The torus plasma flows toward Ganymede's trailing edge, referred to in this paper as the upstream side. At low latitudes, Jupiter's magnetospheric field B is antiparallel to Ganymede's internal field, and reconnection occurs. Within the magnetosphere, the flux tubes that reconnect upstream flow over the polar caps and reconnect again downstream. Low-latitude flow returns flux to the upstream magnetosphere. These flow directions are consistent with an electric field $E_G$ oriented radially outward from Jupiter.

Volwerk et al., JGR, 1999

# III3. Ganymede's Magnetosphere: Field Line Topology

Khurana et al., Icarus, 2007

3 types of field lines:

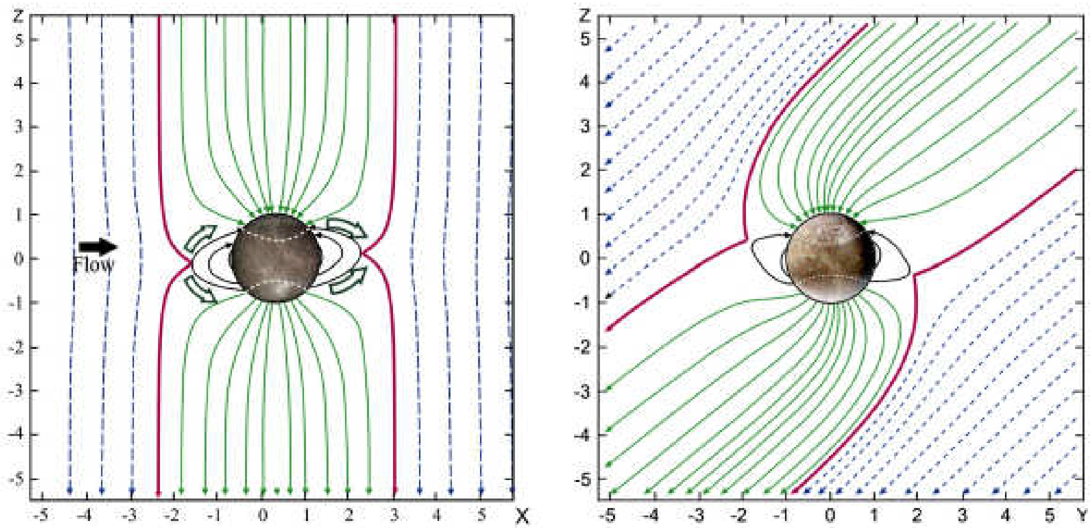



Fig. 1. The configuration of Ganymede's magnetosphere in the $X-Z$ (left) and $Y-Z$ (right) planes. The $x$-axis is parallel to the corotation direction (effectively parallel to the Ganymede orbital direction), $y$ is positive inward toward Jupiter, and $z$ is parallel to the spin axis of Jupiter (effectively parallel to the Ganymede spin axis). Red lines show the last fully open field lines that are connected at both ends to Jupiter. Open arrows mark the path of newly opened field lines, and the dark arrow marks the direction of jovian magnetospheric flow.

Outside the **magnetopause**: **field lines connected to Jupiter's ionosphere at both ends**
(= solar wind field lines at Earth)

Within the magnetosphere: **closed field lines connected to Ganymede at both ends**
(= low-latitude field lines at Earth, 30-40° latitude)

**Field lines connected to Ganymede at only one end and to Jupiter at the other end**
(linked to Ganymede's polar caps like the polar cap field lines at Earth)

# III4. Implication for the design of the JGO

Khurana et al., Icarus, 2007

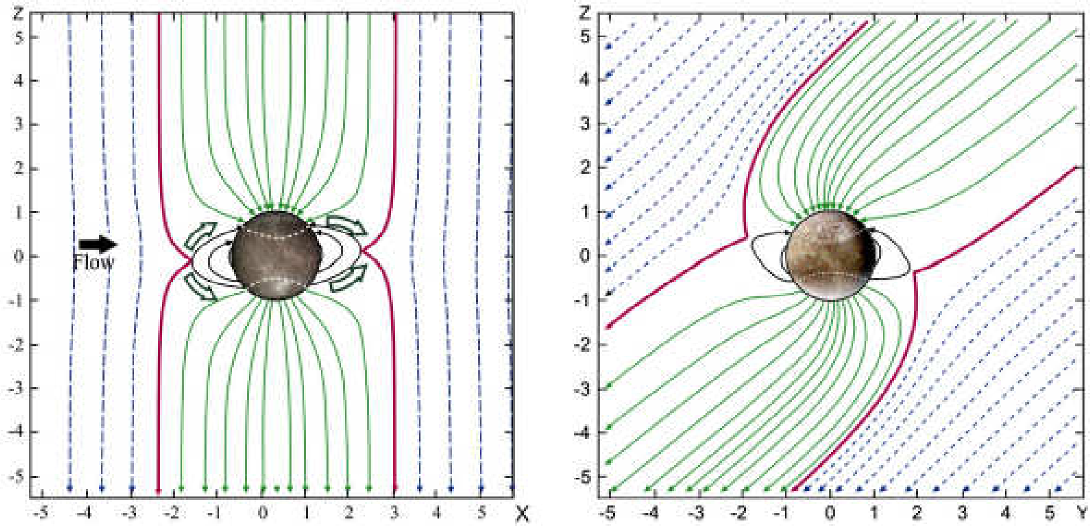



Fig. 1. The configuration of Ganymede's magnetosphere in the $X$–$Z$ (left) and $Y$–$Z$ (right) planes. The $x$-axis is parallel to the corotation direction (effectively parallel to the Ganymede orbital direction), $y$ is positive inward toward Jupiter, and $z$ is parallel to the spin axis of Jupiter (effectively parallel to the Ganymede spin axis). Red lines show the last fully open field lines that are connected at both ends to Jupiter. Open arrows mark the path of newly opened field lines, and the dark arrow marks the direction of jovian magnetospheric flow.

When in orbit around Ganymede:

The JGO spacecraft (~polar, 86° ) will encounter different field lines topology and, hence, different radiation doses.

# III5. Ganymede's Magnetosphere: Upstream Conditions

Ganymede's magnetosphere is embedded in a sub-Alfvenic flow

⇒ Magnetic pressure rather than plasma pressure confines Ganymede's magnetosphere

Jupiter's magnetic moment tilts 10° from its spin axis

⇒ Orientation and magnitude of the field and plasma properties near Ganymede's orbit vary with the 10.5 hour synodic period of Jupiter's rotation

⇒ Ganymede's magnetosphere changes shape in a periodic and predictable manner

Varying external field and plasma environment

⇒ A conductor located within Ganymede (global subsurface ocean) generates a dipolar induction response

# III6. Ganymede's Magnetosphere: Upstream Conditions

Ganymede's magnetosphere changes shape in a periodic and predictable manner

Fluxes of energetic plasma are lower by a factor of 3-5 in regions outside of Jupiter's plasma sheet compared to values inside the plasma sheet

⇒ Most intense bombardment when Ganymede is located in the middle of the plasma sheet near the SIII west longitude of 112° and 292°

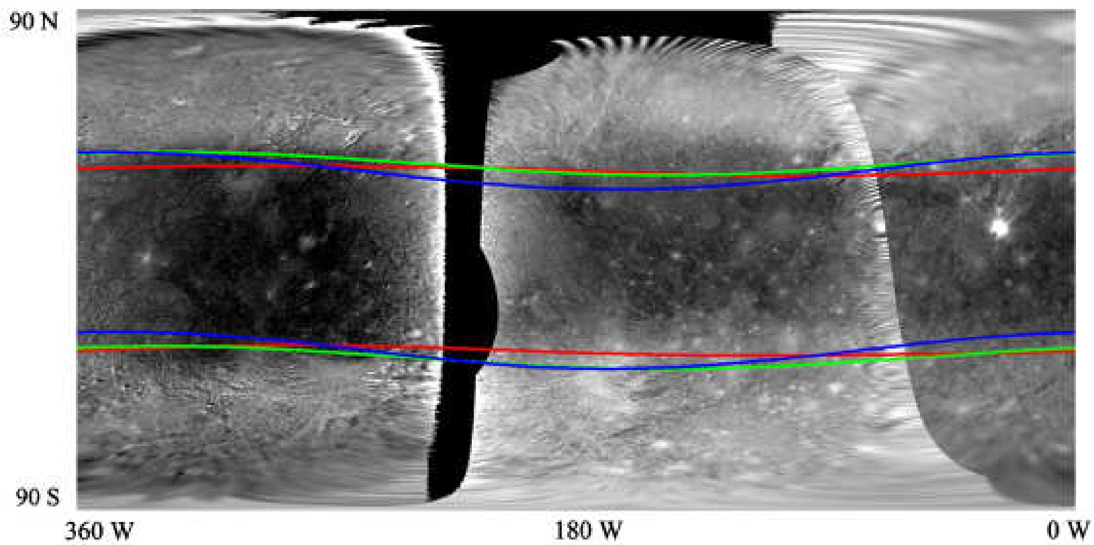
⇒ Ganymede is farthest below the plasma sheet for SIII west longitude of 22°

⇒ Ganymede is farthest above the plasmasheet for SIII west longitude of 202°

Ganymede spends only a short time in the plasma sheet (less than 2 hours) during each synodic rotation period of Jupiter

# III7. Ganymede's Magnetosphere: Illustration

Khurana et al., Icarus, 2007




(b)

Fig. 3. Global image mosaics of Ganymede and predicted locations of the open/closed field line (OCFL) boundary. (a) Mosaic of Voyager and Galileo clear filter (broadband) images at a variety of resolutions. (b) Green/violet ratio composite image of Galileo color data from orbits E14 (west, 10.4 km/pixel), G1 (central, 13.1 km/pixel), and C10 (east, 7.3 km/pixel green and 14.7 km/pixel violet). Superimposed are the OCFL boundaries for three different configurations: red, when Ganymede is farthest above Jupiter's plasma sheet, green when Ganymede is located in the middle of the plasma sheet, and blue when Ganymede is located farthest below the plasma sheet. Image mosaics are in simple cylindrical projection and were produced by the U.S. Geological Survey, Flagstaff, Arizona.

Ganymede's polar regions are brightened in response to being open to jovian plasma

Leading/trailing hemispheric asymmetries at lower latitudes (closed field lines)

# III8. Galileo Ganymede Flybys

6 Ganymede flybys during the Galileo mission

Kivelson et al., Icarus, 2002

TABLE I
Information Regarding Galileo's Encounters with Ganymede

| Pass | Date | C/A UT | LT | Alt. (km) | Planetocentric[a] | | Location[b] | Background field[c] | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Lat. (°) | Long. (°) | rel. to ps | $B_X^{bg}$ | $B_Y^{bg}$ | $B_Z^{bg}$ |
| G1 | 06/27/96 | 0629:07 | 11.27 | 838 | 30 | 247 | above | 6 | −79 | −79 |
| G2 | 09/06/96 | 1859:34 | 10.78 | 264 | 79 | 236 | above | 17 | −73 | −85 |
| G7 | 04/05/97 | 0709:58 | 19.74 | 3105 | 56 | 270 | below | −3 | 84 | −76 |
| G8 | 05/07/97 | 1556:09 | 8.11 | 1606 | 28 | 55 | center | −11 | 11 | −77 |
| G28 | 05/20/00 | 1010:10 | 0.78 | 900 | −13 | 59 | below | −7 | 78 | −76 |
| G29 | 12/28/00 | 0858 | 23.9 | 2320 | 62 | 259 | above | −9 | −83 | −79 |

[a] Planetocentric location is provided with East longitude measured from the prime meridian plane centered on the Jupiter-facing side.
[b] This column describes Ganymede's location relative to the center of Jupiter's magnetospheric plasma sheet at the time of the pass.
[c] These columns are estimates of the components of the background field at the location of Ganymede at the time of the pass. They are obtained by fitting a polynomial to the field measured before and after the perturbations associated with the Ganymede encounter appear in the data and are given in a Ganymede-centered Cartesian coordinate system that we refer to as GphiO.

G1:No EPD data, Ganymede above the center of the plasmasheet
G2: polar, CA~264 km, Ganymede above the center of the plasmasheet
G7: wake, Ganymede below the center of the plasmasheet
G8: upstream, Ganymede in the center of the plasmasheet
G28: Ganymede below the center of the plasmasheet
G29: Ganymede above the center of the plasmasheet

# III9. Ganymede Flybys

To understand the next slides:

Galileo EPD instrument:

spectral and angular distributions
of ions above 20 keV

spectral and angular distributions
of electrons above 15 keV

Only data from 2 channels represented

The remaining channels show the same features, albeit with varying sensitivity and clarity

Galileo Ganymede Flyby Trajectories (GphiO)

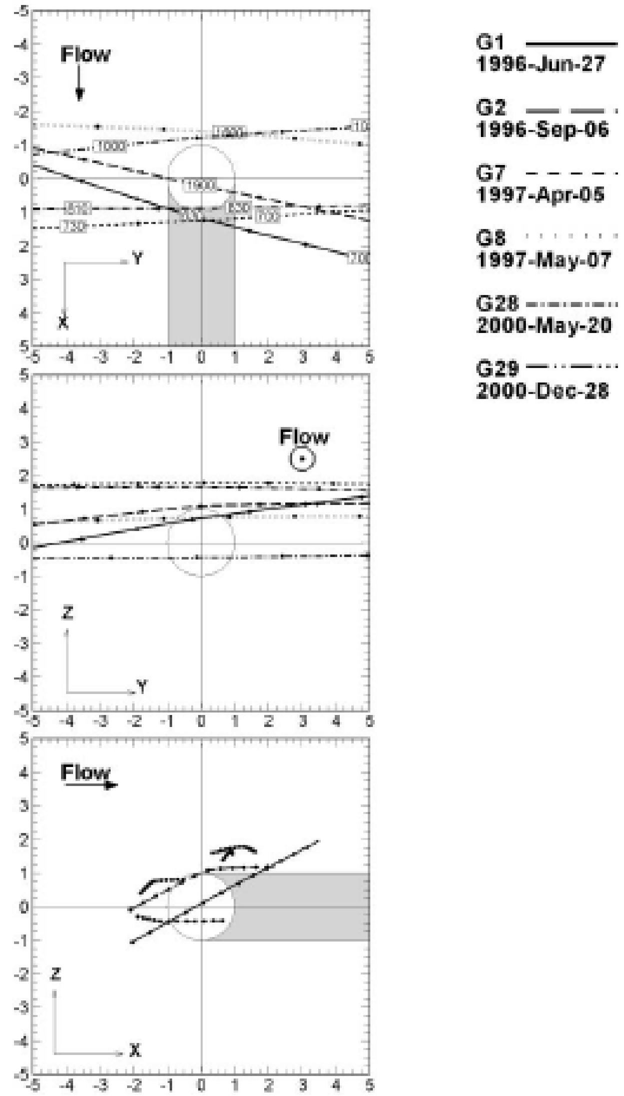



FIG. 1. Plots of Galileo's passes by Ganymede. The coordinate system is defined in the text.

# III10. Galileo EPD Data: G2

Williams et al., JGR, 1998

In blue:
The counts corresponding to the Jovian plasma

In red:
Inside Ganymede's magnetosphere

Spike-like decreases observed for ions and electrons:

=> We were on field lines connected to both Ganymede and jupiter

Clear decrease observed inside Ganymede's magnetosphere by a factor up to 10 !

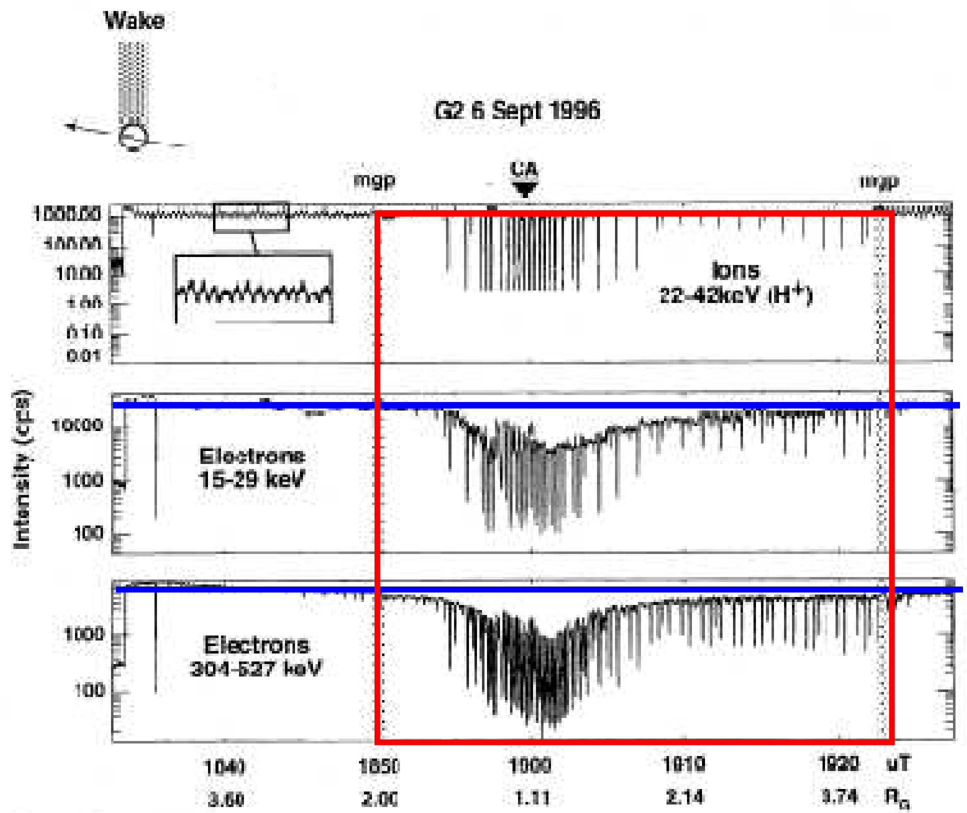



Figure 1. Energetic ion and electron intensities during the Galileo satellite's G2 encounter with Ganymede. The data shown are representative of the observations from all EPD ion, species, and electron channels. Magnetometer magnetopause locations are shown at the top of the figure, and the geometry of the encounter projected into Jupiter's corotation plane is given in the upper left portion of the figure. Spin modulation of the ion intensities (shown amplified in the insert) due to corotational convective flow anisotropies is seen prior to entry into Ganymede's magnetosphere and following exit. The spike-like decreases within Ganymede's magnetosphere are loss cone signatures.

# III11. Galileo EPD Data: G7

Williams et al., JGR, 1998

In blue:
The counts corresponding
to the Jovian plasma

In red:
Inside Ganymede's magnetosphere

Spike-like decreases observed
for ions and electrons again

=> We were on field lines connected
to both Ganymede and jupiter

Clear decrease observed
inside Ganymede's magnetosphere
by a smaller factor / G2

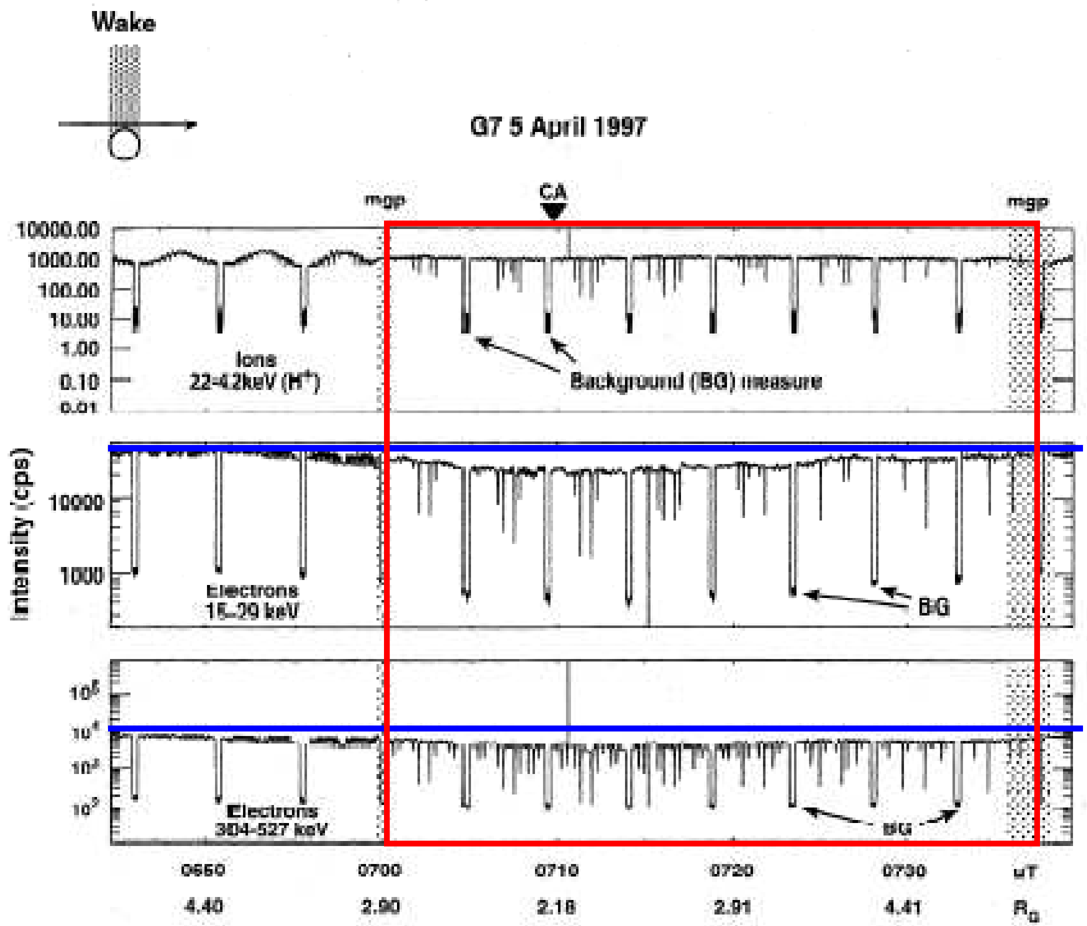



**Figure 2.** The Galileo G7 encounter in the same format as Figure 1. The different perspective results from both the different encounter geometry and the different stepper motor sequence used for EPD during the encounter. Background measurements are identified. The data show similar corotational convective flow anisotropy changes and loss cone signatures as are seen in the G2 encounter.

# III12. Galileo EPD Data: G8

Williams et al., JGR, 1998

In blue:
The counts corresponding to the Jovian plasma

In red:
Inside Ganymede's magnetosphere

Spike-like decreases observed for ions and electrons again

=> We were on field lines connected to both Ganymede and jupiter

Clear decrease observed inside Ganymede's magnetosphere by a higher factor compared to G2

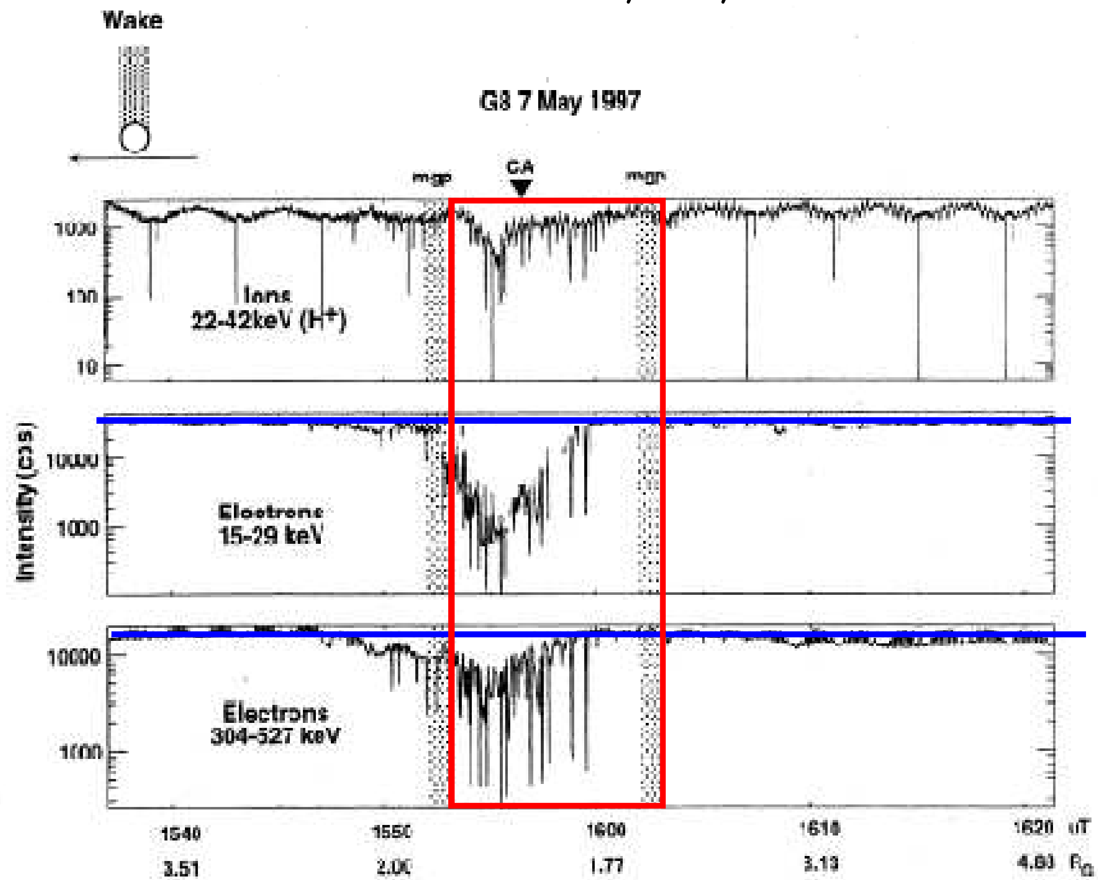



Figure 3. The Galileo G8 encounter in the same format as Figure 1. Again, the corotational convective flow anisotropy changes and loss cone signatures are similar to those seen in Figures 1 and 2. However, for the G8 encounter, ion intensities show a substantial decrease within Ganymede's magnetosphere in contrast to the G2 and G8 encounters. Also, electron intensities decrease much more in G8 than in G2 or G7. This indicates that the region of the Ganymede magnetosphere entered in G8 provided a higher degree of shielding from the ambient Jovian environment.

# III13. EPD Data: G28

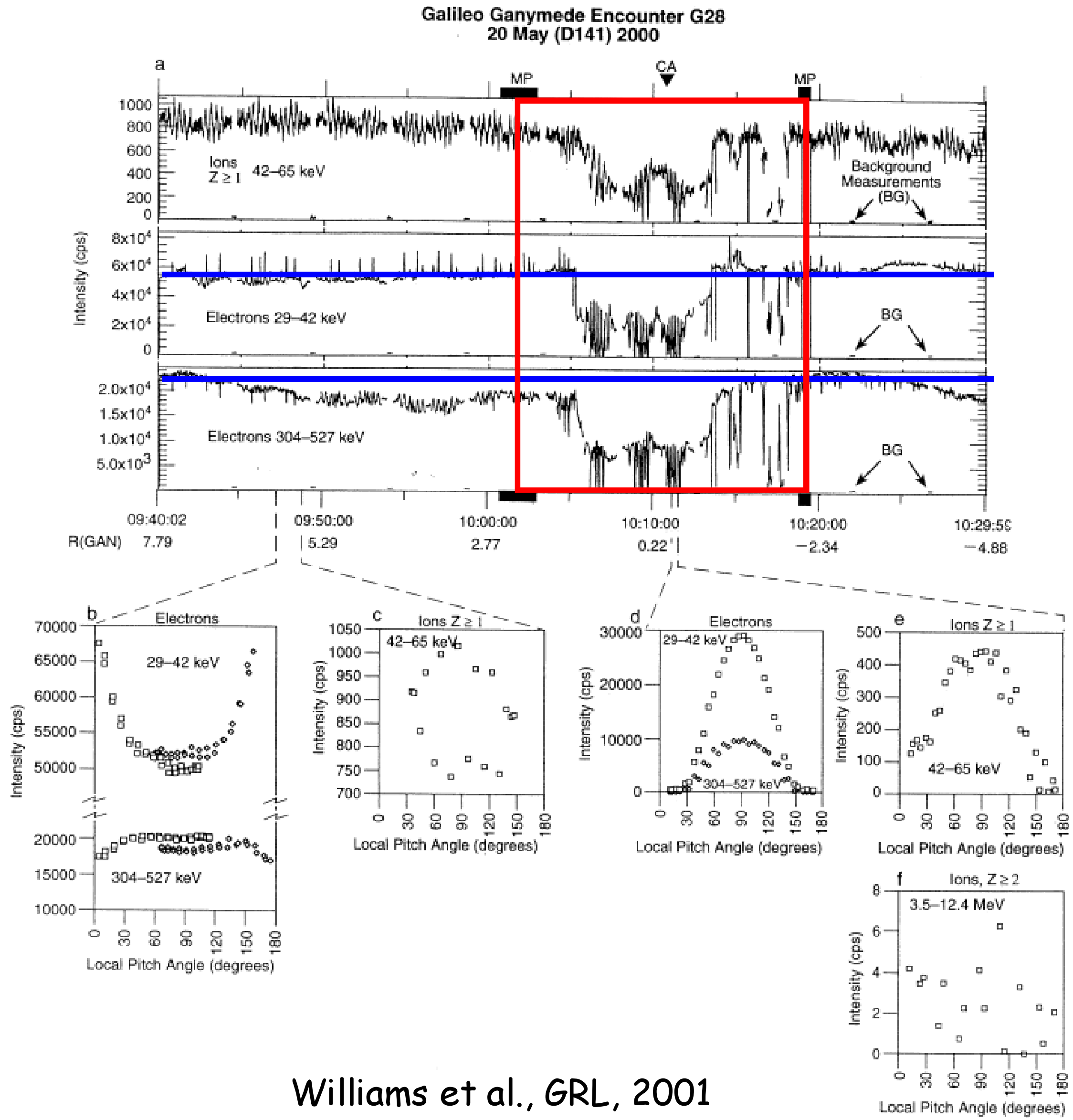
Spike-like decreases observed for ions and electrons again

=> We were on field lines connected to both Ganymede and jupiter

Clear decrease observed inside Ganymede's magnetosphere: by a higher factor / G2

Trapped electrons and ions observed (radiation belts) but fluxes are still lower than in the Jovian plasma

=> We were on closed field lines




Williams et al., GRL, 2001

# III14. EPD Data: G29

Spike-like decreases observed
for ions and electrons again

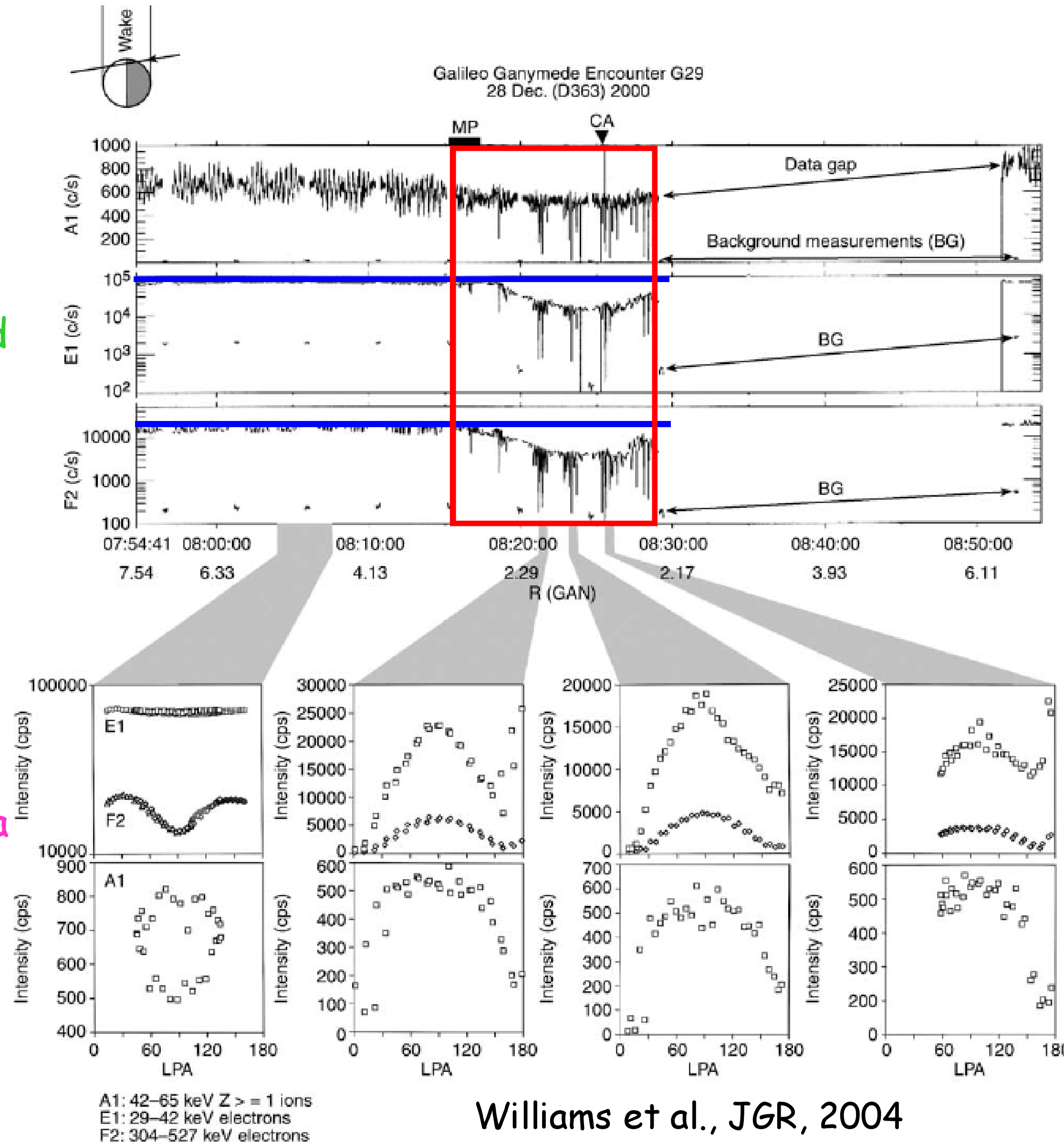
=> We were on field lines connected
to both Ganymede and jupiter

Clear decrease observed
inside Ganymede's magnetosphere:
by a smaller factor / G2

Trapped electrons and ions again
(radiation belts) but fluxes are
still lower than in the Jovian plasma

=> We were on closed field lines

A dynamic magnetosphere
was observed
(electron beams at low energy)




Williams et al., JGR, 2004

# III15. Implication for the design of the JGO

Ion and electron intensities decrease substantially
at entry into Ganymede's magnetosphere, as observed during ALL the flybys

$\Rightarrow$ Lower fluxes compared to the Jovian plasma

The radiation doses estimated by Mission Analysis correspond to the ones obtained by considering the fluxes in the Jovian plasma (blue lines in previous slides)

The observed decreases are SIGNIFICANT (at least a factor 3, up to 10)

Therefore we largely OVERESTIMATE the radiation doses at the moment for the design of the JGO, during the orbital phase around Ganymede

This is what the data tells us so far …

# IV. Future Steps

# IV1. Future Steps

Re-analyze Galileo EPD data obtained during all Ganymede flybys to estimate quantitatively the reduction in radiation doses

Eviatar et al., JGR, 2001

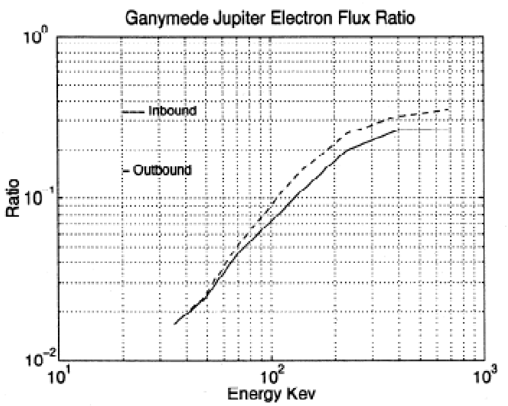



**Figure 5.** Ratio of the electron intensities observed on Ganymede 8 at closest approach to those observed in the ambient Jovian magnetosphere just before crossing the Ganymede magnetopause, as a function of energy. The nearly 45° slope of the curves appears to implicate magnetic gradient drift in causing the observed phenomena.

Work with Chris Paranicas (APL/JHU) on estimating the obscuration effects at Ganymede, as done in the case of Europa ?

Work with John Cooper (NASA/GSFC) on his detailed modelling of the radiation environment of Ganymede's magnetosphere ?

# IV2. Future Steps

Workshop during the next Europlanet conference:

Designing new missions to the Jupiter and Saturn systems:
Modelling of their plasma, dust and radiation environments

Invited speakers

but

You are all welcome to participate and attend of course ! (Deadline: June, 13)