# Charged Particle Fluxes and Radiation Doses in Earth-Jupiter-Europa Spacecraft's Trajectory

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- Models of Jupiter's radiation belts and satellite experiments near Jupiter
- Charged particle fluxes and radiation doses in Europa orbit
- Charged particle fluxes and radiation doses during the gravity assists near Jupiter
- Radiation environment in the interplanetary part of the trajectory
- Proposals for radiation environment control during the mission
- Conclusions, discussion

# Models of Jupiter's radiation belts

N. Divine, Jupiter Radiation Belt Models, Techn. Mem. 33-715, 1974, 13 p. /1st model, used Pioneer 10 data/

R. W. Fillius, C. E. McIlwain, A. Mogro-Campero, Radiation Belts of Jupiter: A Second Look, Science, v. 188, 1975, p. 465–467. /An update of the model, using Pioneer 11 data/

N. Divine, H. B. Garrett, Charged Particle Distributions in Jupiter's Magnetosphere, J. Geophys. Res., v. 88, No 9, 1983, p. 6889–6903. /Model, based on the data from Pioneer 10, 11 and Voyager 1, 2/

M. H. Acuna, N. F. Ness, The main magnetic field of Jupiter, J. Geophys. Res., 81, 1976, p. 2917–2922. /The "O4" Jupiter's magnetic model, 15 Gauss coefficients/

I. V. Getselev, Yu. I. Gubar et al., Radiation Conditions of the Spacecraft Flight in Jupiter's Near-Planetary Space, MSU, VINITI No 4636-84, 1984. (in Russian).

I. V. Getselev, Yu. I. Gubar et al., Model of the Radiation Environment of Jupiter's Artificial Satellites, MSU, VINITI No 8970B, 1985. (in Russian).

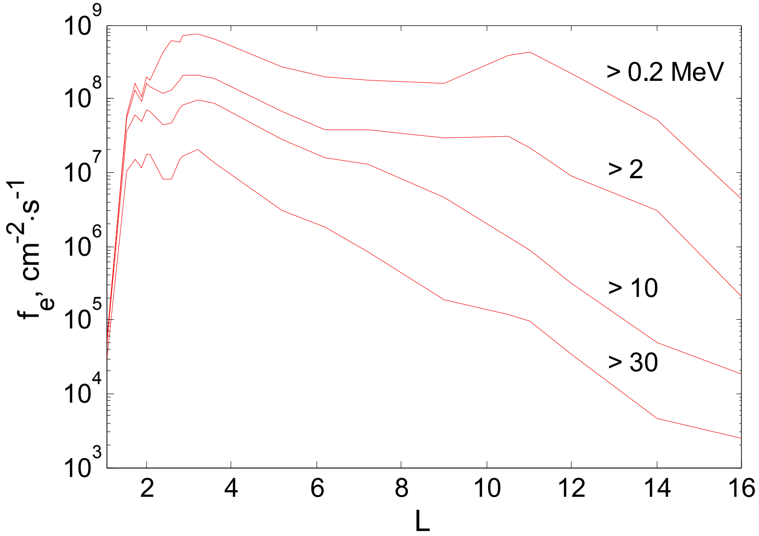
Yu. I. Gubar, A. R. Mozzhukhina, I. S. Veselovsky, The Expected Radiation Doses for the Flight of S/C "Solar Probe" through the Jovian Magnetosphere, Proc. 1st US-Russian Scientific Workshop on FIRE Environment, SRI, Moscow, 1995, p. 213–215. /Values obtained using Getselev-Gubar model agree with NASA computations/

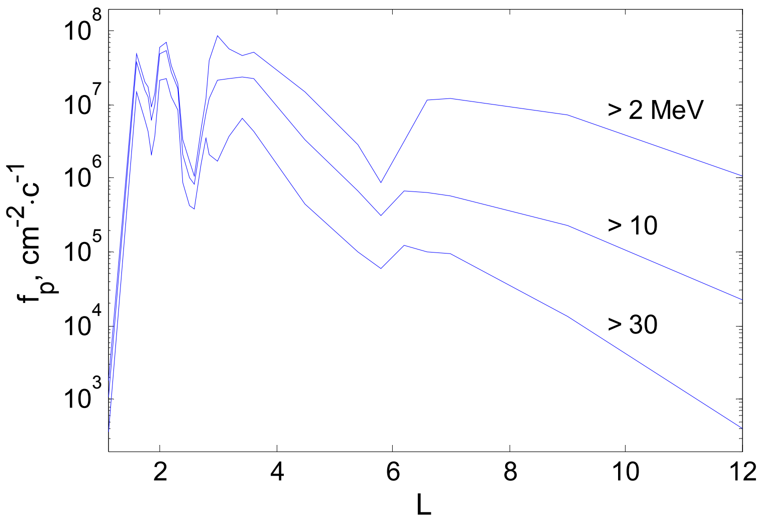
H. B. Garrett, S. M. Levin, S. J. Bolton, A Revised Model of Jupiter's Inner Electron Belts: Updating the Divine Radiation Model, Geophysical Research Letters, v. 32, L04104, 2005, 5 p. /A revision of Divine-Garrett model for high-energy electrons at $L < 4$ from Galileo and synchrotron observations/

# Magnetosphere and charged particles satellite measurements at Jupiter

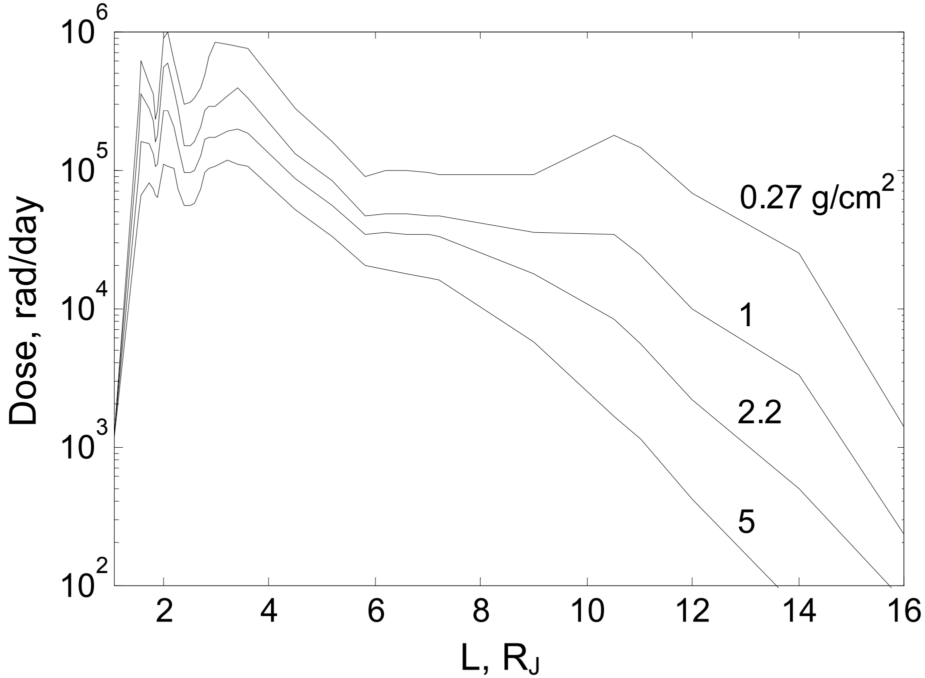
| mission | time | orbit | experiments | doses |
|---|---|---|---|---|
| Pioneer 10 | Dec. 1973 | Fly-by at 130 ths. km from Jupiter (2.8 $R_J$) | Magnetic field, electrons: 0.06 to >35 MeV, protons: 0.6 to >80 MeV | $5 \cdot 10^5$ rad electrons and $1 \cdot 10^6$ rad protons on the surface, $4.5 \cdot 10^5$ rad at 3 mm Al |
| Pioneer 11 | Dec. 1974 | Fly-by at 43 ths. km (1.6 $R_J$), high incl. orb. | | $1.3 \cdot 10^5$ rad electrons, $3 \cdot 10^5$ rad protons on the surface, $1.2 \cdot 10^5$ rad at 3 mm Al |
| Voyager 1 | March 1979 | Fly-by at 207 ths. km (4 $R_J$) | Magnetic field, low-energy particles, electrons: 3–110 MeV, ions: 1–500 MeV/nucl | $\approx 5 \cdot 10^5$ rad |
| Voyager 2 | July 1979 | Fly-by at 570 ths. km (9 $R_J$) | | |
| Ulysses | Feb. 1992 | Fly-by at 378 ths. km (6.3 $R_J$), high incl. orb. | Magnetic field, energetic particles | estim. $6 \cdot 10^4$ rad (inside?) |
| Galileo | 1995–2003 | 35 highly elliptical orbital segments with $r_\pi$ typically 6–11 $R_J$ | Magnetic field, electrons: 15 keV to >11 MeV, Ions: 10 keV to 200 MeV/nucl | Designed for 150 krad at 2.2 g/cm$^2$, sustained >650 krad; “remarkably healthy”, but damaged some electronic systems |
| Cassini | Nov. 2000 | Fly-by at 10 mln. km (140 $R_J$) | Magnetic field sync. w/Galileo, high-energy electrons (radiation spectrometer) | |

# Charged particle flux and radiation dose equatorial profiles at Jupiter



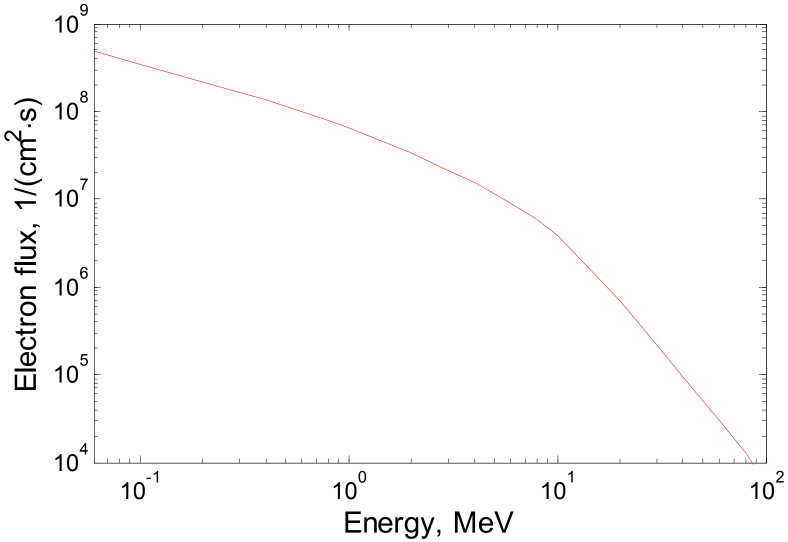

Equatorial profiles of the integral fluxes of E >0.2, >2, >10 and >30 MeV electrons and E >2, >10 and >30 MeV protons at Jupiter.



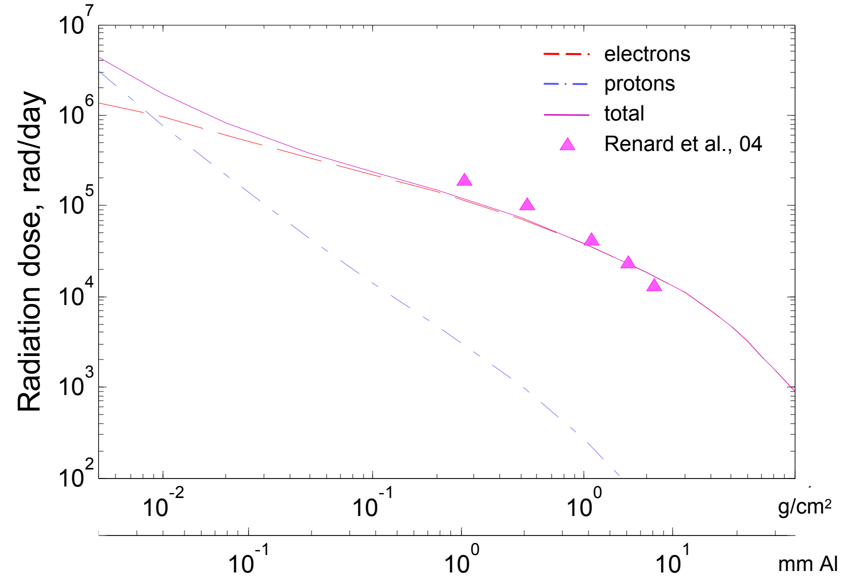


Equatorial profiles of radiation doses under 0.27, 1, 2.2 and 5 g/cm$^2$ shielding near Jupiter.

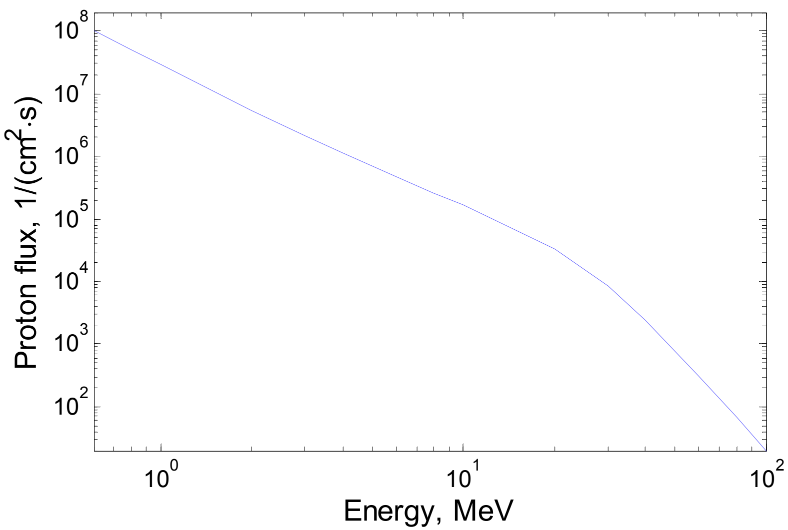
# Calculated radiation doses in Europa orbit: high hazard




Electron integral spectra in Europa orbit




Doses under various shielding from electrons (dashed line), protons (dash-dot line) and total dose (solid line); also the doses from Renard et al. (2004) are given (triangles).

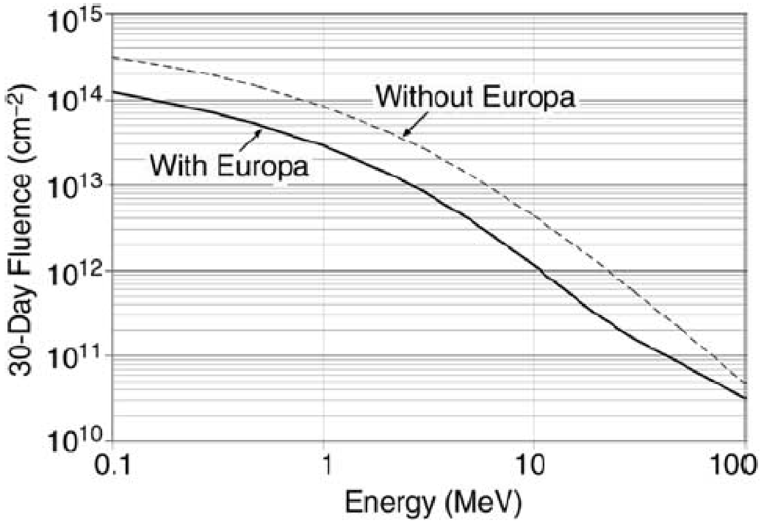



Proton integral spectra in Europa orbit

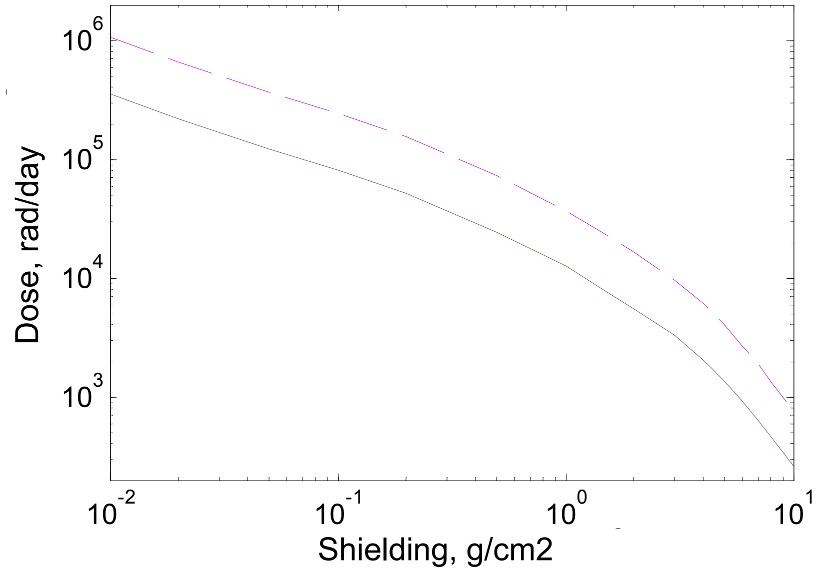
Total 2-month doses in Europa orbit (at 9.5 $R_J$)

| g/cm² | rad | g/cm² | rad |
|---|---|---|---|
| 0.00 | $8.5 \cdot 10^8$ | 1.0 | $2.2 \cdot 10^6$ |
| 0.01 | $1.0 \cdot 10^8$ | **2.2** | **$8.8 \cdot 10^5$** |
| 0.10 | $1.5 \cdot 10^7$ | **5.0** | **$2.4 \cdot 10^5$** |
| 0.27 | $7.4 \cdot 10^6$ | 10.0 | $4.5 \cdot 10^4$ |

# Average fluxes of electrons near Europa




Mean 2-month electron fluxes taking into account Europa influence (C. Paranicas et al., Europa's Near-Surface Radiation Environment, Geophys. Res. Letters, v. 34, 2007).




Mean doses with and without taking into account Europa influence.

Total 2-month doses in Europa orbit

| $g/cm^2$ | w/o Europa | with Europa |
|---|---|---|
| 1.0 | $2.2 \cdot 10^6$ | $7.4 \cdot 10^5$ |
| **2.2** | $\mathbf{8.8 \cdot 10^5}$ | $\mathbf{2.9 \cdot 10^5}$ |
| **5.0** | $\mathbf{2.4 \cdot 10^5}$ | $\mathbf{8.1 \cdot 10^4}$ |
| 10.0 | $4.5 \cdot 10^4$ | $1.5 \cdot 10^4$ |

# Factors that determine charged particle flux reduction near Europa

– "directly" blocking of the particles by Europa;
It depends on the latitude, more exactly — from the angle between the force line and the surface.

– the ratio between the drift speed relative to Europe, and the bounce period;
E.g. 30 MeV electron flux on the surface is equal to zero, 5–30 MeV electrons do not reach the leading side.

– distortion of Jupiter's magnetic field near Europa;

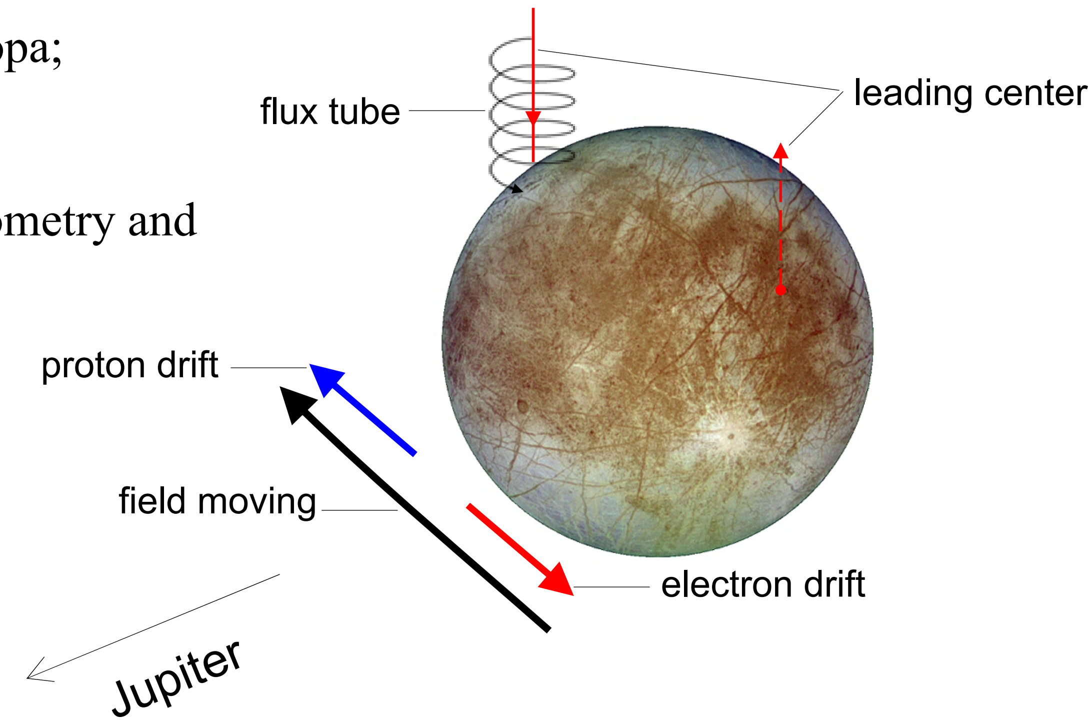
– presence of the electric field;

– difference of Europa orbit plane from the plane of Jupiter's magnetic equator;

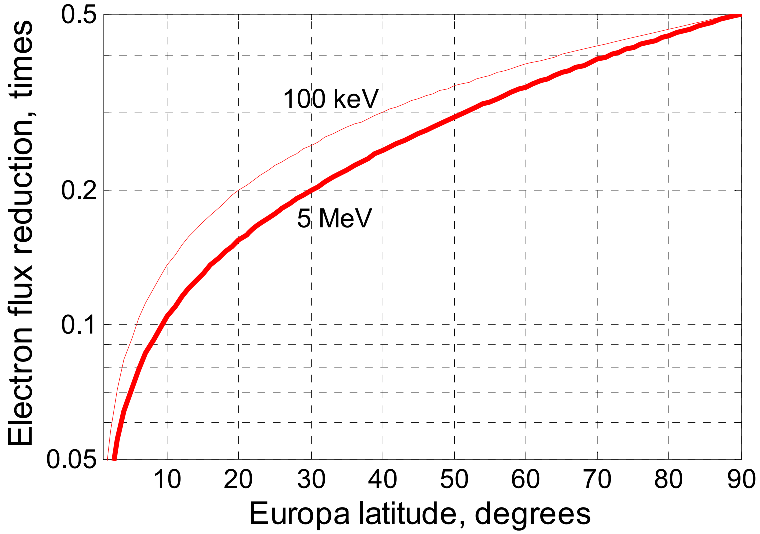
– atmosphere and ionosphere of Europa;

– presence of the electric field;

– the exact information about the geometry and the thickness of the shielding



# Dependence of electron flux reduction from the surface point latitude



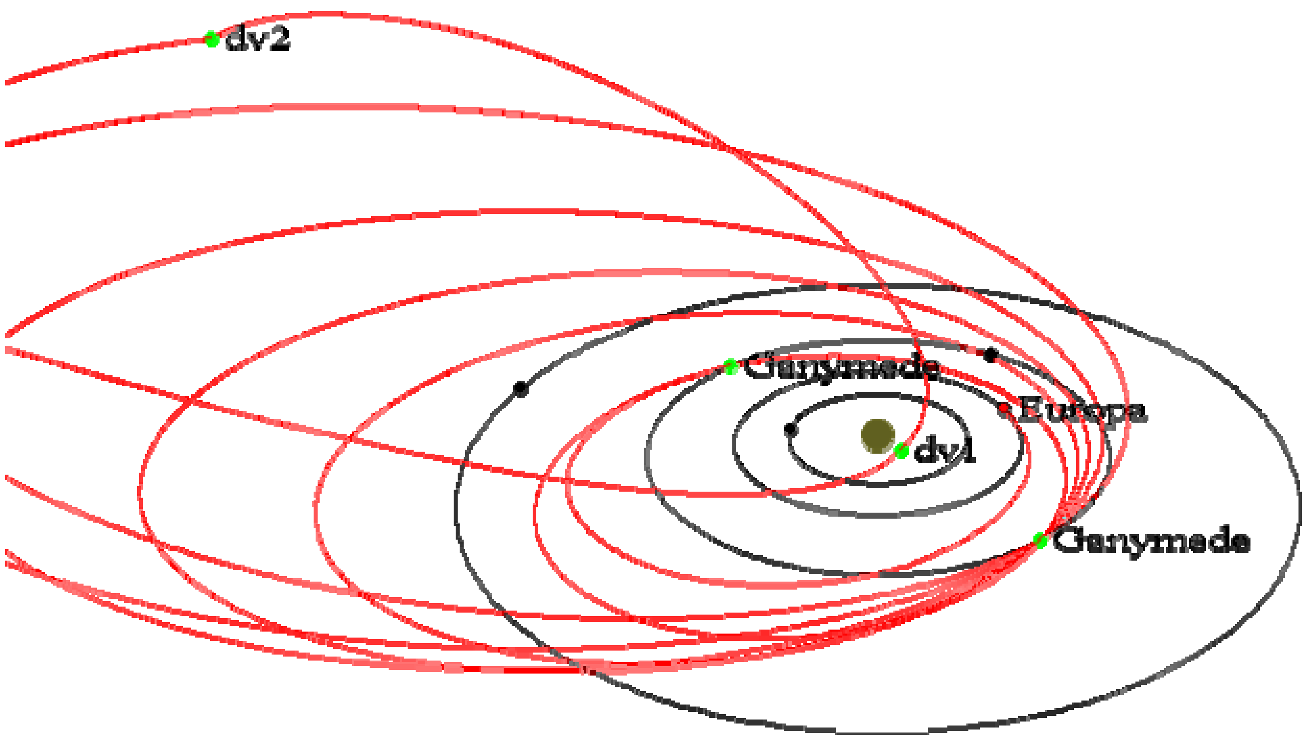

Dependency of the 100 keV (thin curve) and 5 MeV (bold curve) electron flux reduction on Europa surface from the latitude (more exactly — from the angle of the magnetic field line with the surface). The type of the dependence is the same for both energies; difference between two curves result from the difference of the pitch-angle distributions for these energies. But for energies over 5–10 MeV the type of the dependency will somewhat differ.

# Gravity assists near Jupiter and its Galilean satellites

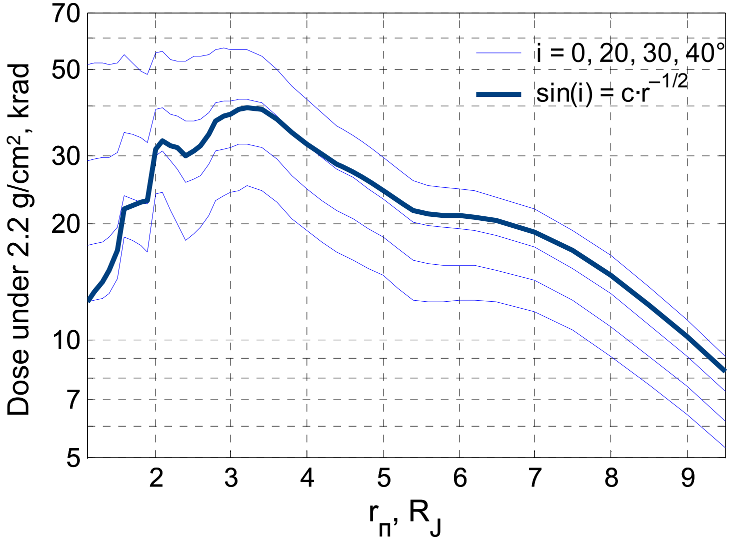
We consider the gravity assists contain the next stages:

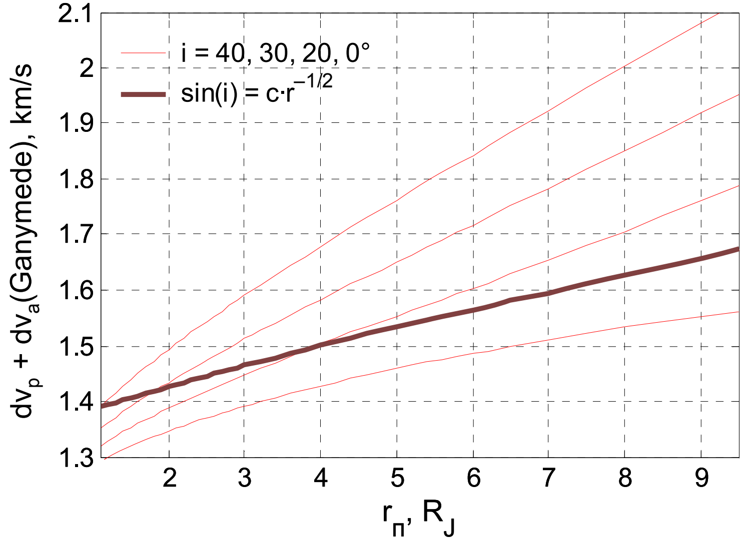
- 1st fly-by near Jupiter, firing the engine in the pericenter and coming to high-elliptical orbit;
- 2nd firing the engine in its apocenter, to turn the orbit plane to Jupiter's equatorial plane, and to rise the pericenter to the orbit of Io or Ganymede;
- several gravity assists at Galilean satellites to lower spacesraft orbit to the orbit of Europa;
- and finally 3rd impulse by the engine and coming to the orbit around Europa.

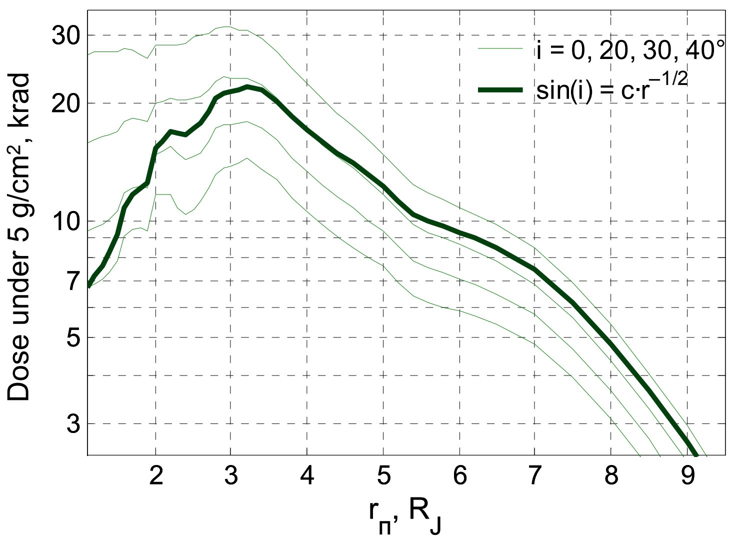
**The problem is: to optimize both the fuel consumption and the radiation dose.**

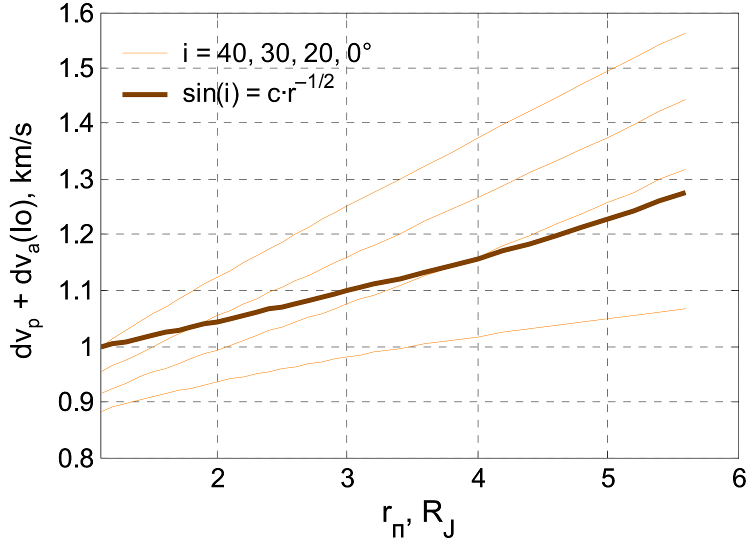


# Dependence of doses and impulses on the 1st fly-by from pericenter distance




Doses on the 1st fly-by under 2.2 $g/cm^2$ (top) and 5 $g/cm^2$ (bottom) depending on the pericenter distance r for the inclination i = 0, 20, 30, 40° and $\sin(i) = c \cdot r^{-1/2}$.

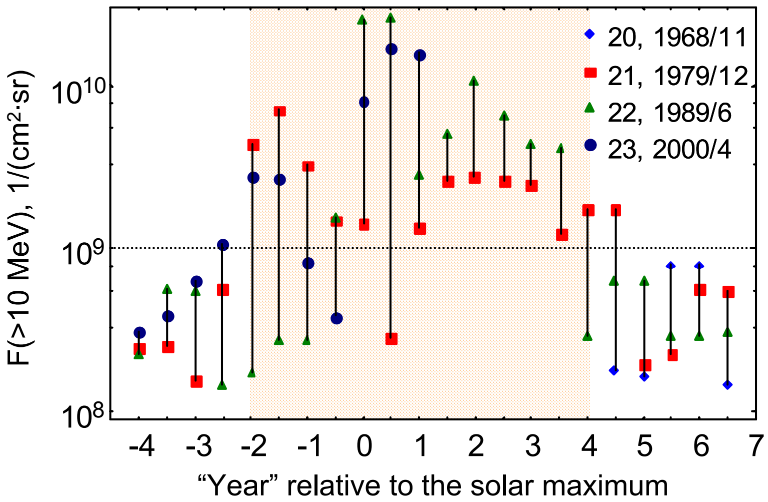
Sum of the impulses $dv_p + dv_a$ in pericenter and apocenter of the 1st circuit for the next curcuit near Ganymede (top) and Io (bottom) depending on r for i = 0, 20, 30, 40° and $\sin(i) = c \cdot r^{-1/2}$.

# Parameters of different variants of gravity assists near Galilean satellites

| gravity assists scheme | t | dvi1 | dvi2 | dose, except 1st fly-by, krad | | | | $t_{rad\ belt}$ |
|---|---|---|---|---|---|---|---|---|
| | days | km/s | | 1 g/sm$^2$ | 2.2 | 5 | 10 | days |
| 1. IIIIIIIIIIGGGE | 347 | 1.410 | 2.569 | 1487 | 803 | 364 | 94 | 71 |
| 2. IIIIIIIIIIGGGEGEGE | 358 | 1.081 | 2.073 | 1642 | 853 | 376 | 96 | 82 |
| 3. IIIIIIIIIIGGGEGEGEGE | 364 | 1.080 | 2.070 | 1717 | 876 | 382 | 98 | 88 |
| **11. GGGGGGE** | **293** | **1.620** | **2.857** | **103** | **25** | **5** | **1.2** | **14** |
| 12. GGGGGGGGIIGGGGE | 390 | 1.292 | 2.339 | 1599 | 731 | 273 | 63 | 99 |
| 13. GGGGGGGIIGGGE | 347 | 1.292 | 2.339 | 1048 | 504 | 197 | 46 | 66 |
| 15. GGGGGEEGE | 402 | 1.091 | 2.090 | 1433 | 445 | 107 | 22 | 107 |
| **16. GGGGGE** | **335** | **1.620** | **2.860** | **103** | **25** | **5** | **1.2** | **14** |

# Cosmic ray protons in the interplanetary space during the mission

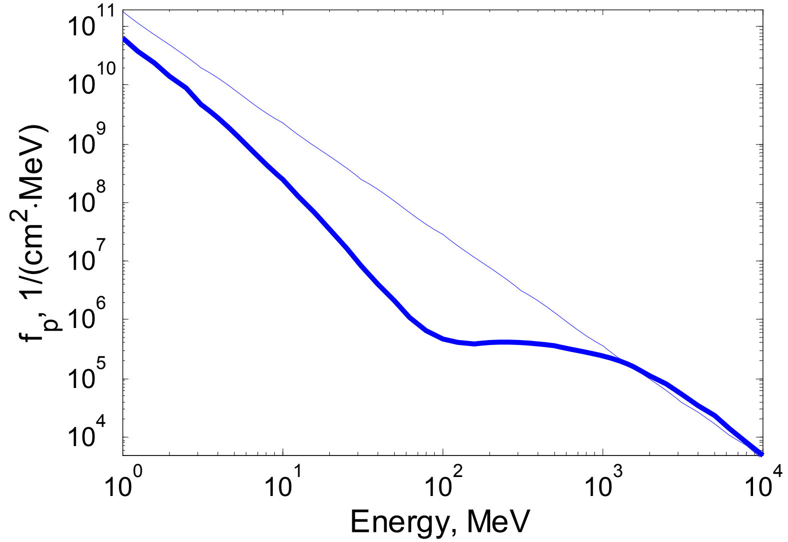
The mission will star in 2017–2020. The 24th cycle maximum will be in 2011–2012, thus the flight will mainly take place during the quiet Sun.




In the active cycle phase 1-year cosmic ray proton fluences are higher, and in the passive — lower, than threshold level, correspond to overall $p$ = 0.5.

Total doses for the interplanetary path, rad

| g/cm² | prediction | upper est. |
|---|---|---|
| 1.0 | $3.8 \cdot 10^1$ | $1.2 \cdot 10^3$ |
| **2.2** | **$1.5 \cdot 10^1$** | **$5.5 \cdot 10^2$** |
| **5.0** | **$9.1 \cdot 10^0$** | **$2.5 \cdot 10^2$** |
| 10.0 | $7.5 \cdot 10^0$ | $1.3 \cdot 10^2$ |



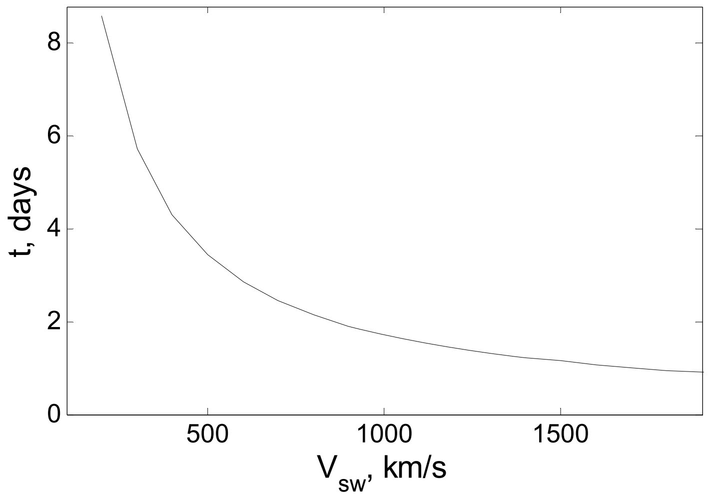

Total differential interplanetary proton fluxes for "EVEEJ" variant of trajectory; start in 2017, reach Jupiter in 2022, last 5.6 year.

1) Thin solid line — upper estimate, using simple model (Podzolko, Getselev, 2005) of the total solar and galactic proton flux in Earth's orbit.

2) Bold line — prediction, using (Nymmik, 1999) for SCR solar, and (ISO 15390, 2004) for galactic protons. Time relative to the beginning of the cycle and the distance from the Sun have been taken into account; "typical" solar cycle was considered.

"Galileo" was launched on October 18, 1989, right during the 22rd cycle maximum. Received 50 krad under 2.2 g/cm² during the interplanetary flight.

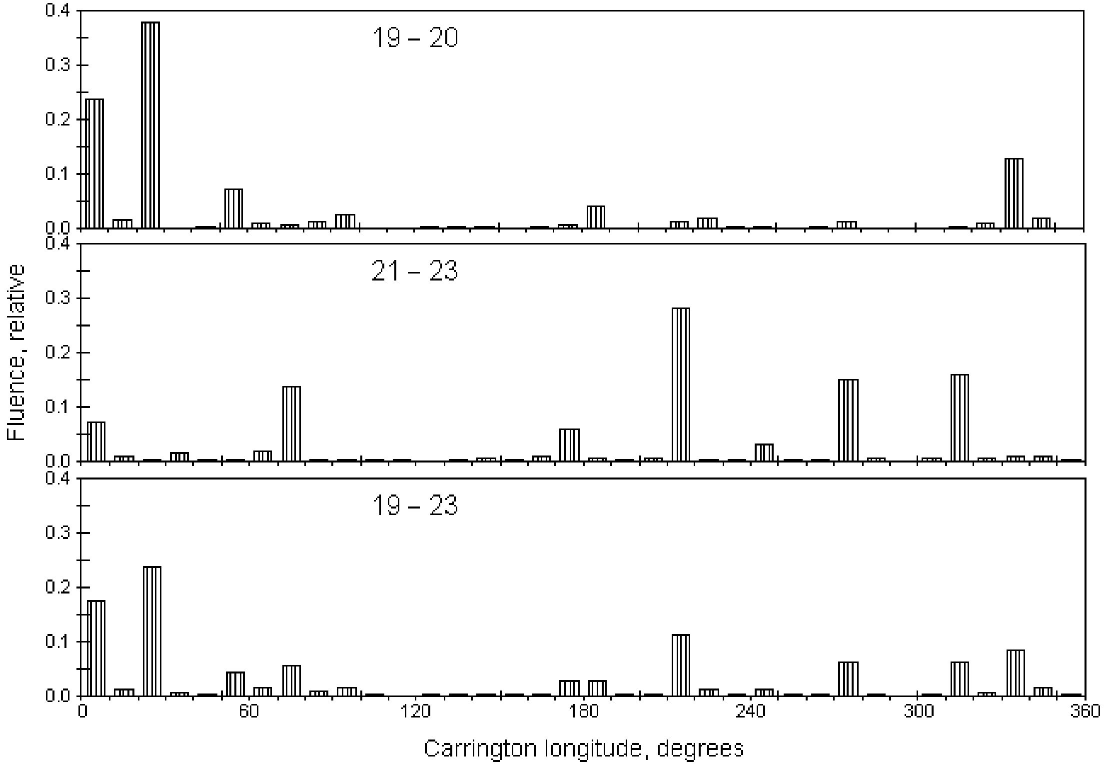
# Solar wind and interplanetary magnetic field during the mission




Main parameters are solar wind proton density and speed, temperature, magnitude of the magnetic field and its components. The density and $B_x$ depends from the heliocentric distance as $R^{-2}$, other – as $R^{-1}$. Speed and temperature can be considered constant with 10% accuracy from 1 AU to Jupiter's orbit (5.2 AU). The mean parameters depends on solar cycle phase within 20%.

Coronal mass ejections and shockwaves in heliosphere weaken and slow down somewhat with increase of R. The slowing is that faster, the higher the disturbance is. For the estimation purposes within the first tens % we may consider the speed being constant In Earth's orbit times vary from ≤ 1 day to 1 week, for Jupiter – from 1 week to 1 month. For accurate computations the MGD-modeling should be used.

For the medium-term forecasts we suggest to use irregularity of the heliolongitude distribution of particle sources on the Sun. In particular we discover a continuous (80–170°) "passive longitudes" interval, that is stable and keeps very "quiet" during the last 5 solar cycles.



# Cosmic ray protons in the interplanetary space during the mission

1. **Control of the radiation onboard spacecraft:** Spectrometer of Linear Energy Transfer (SLET)
   - dosimetry;
   - model of LET and dose distribution for Jupiter from simultaneous multisatellite measurements!
   - need LET spectra to estimate the Single Event Effects (SEE) frequency;
   - inverse task: discover or verify particles spectra from the measured LET spectra

| | |
|---|---|
| mass | ≤ 500 g |
| power | 0.5 W |
| telemetric information | ≤ 250 KB/day |

2. **Radiation in the interplanetary space:** studying the spectra and the dynamics of charged particle fluxes (electrons, protons and Helium ions) on the interplanetary path, in Jupiter's near-planetary region and in Europa orbit: Spectrometer of Charged Particles (SCP)

| | |
|---|---|
| registered particles | electrons: 0.1–4 MeV,<br>protons, He: 1–30, >500 MeV/nucl |
| mass | ≤ 3 kg |
| power | ≤ 4 W |
| telemetric information | ≤ 1 MB/day |

# Conclusions, discussion

- The main radiation hazard during the mission comes from Jupiter's radiation belts. Most of the radiation dose will be received by the spacecraft in Europa orbit and on its surface.
- The factors have been defined, that affect the charged particle flux reduction near Europa and on its surface; they should be taken as the entry parameters for constructing the detailed model of particle fluxes near Europa.
- Gravity assists near Jupiter and its Galilean satellites is also connected with serious radiation hazard. We conclude, that both for the energy consumption issue and for the radiation safety it is optimal to make the 1st gravity assist near Jupiter with the pericenter closer than ~150 thousand km and an inclination of 40° or higher. For the rest of the gravity assists we suggested to use Ganymede, and make the final path between Ganymede and Europe as short, as possible.
- The doses on other parts of the trajectory will be considerably smaller.
- Proposals have been made on monitoring the radiation environment at all stages of the flight.
- Possibly the main conclusion: **working on Europa Lander project we have to solve the complex optimization task, simultaneously taking into account many factors:** radiation, energy consumption, limits on the size and weight of the scientific equipment, data transfer and so on.
- The question of improving the models of Jupiter's radiation belts and magnetic field etc. is still actual.