X-641-73-347
PREPRINT

NASA TM X- 70516

JUPITER'S RADIATION BELTS: CAN PIONEER 10 SURVIVE?

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NOVEMBER 1973

GSFC

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CAN PIONEER 10 SURVIVE?

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To be published in Science

ABSTRACT

Model calculations of Jupiter's electron and proton radiation belts indicate that the Galilean satellites can reduce particle fluxes in certain regions of the inner magnetosphere by as much as six orders of magnitude. Average fluxes should be reduced by a factor of 100 or more along the Pioneer 10 trajectory through the heart of Jupiter's radiation belts in early December. This may be enough to prevent serious radiation damage to the spacecraft.

Concern has been expressed that Jupiter's radiation environment might be so hostile that a spacecraft could not survive a close flyby (1). Recent calculations suggest, however, that three of the Galilean satellites are very effective in limiting the fluxes of energetic electrons and protons diffusing inward from Jupiter's outer magnetosphere. We find these fluxes to be as much as six orders of magnitude smaller than they would be if there were no absorbing moons. Some of our results are shown in Fig. 1, where electron and proton densities with and without the satellites included are plotted as functions of distance from the center of the planet in units of Jovian radii ($1\ R_J \cong 70000$ km). This is a phase space density $\underline{n}$, which is linearly proportional to particle flux $\underline{F}$, so that sharp decreases in $\underline{n}$ imply proportionally sharp decreases in $\underline{F}$. Fig. 1 has one overall arbitrary normalization factor, and only the relative variations of $\underline{n}_p$ and $\underline{n}_e$ with $\underline{R}$ are significant. Note the precipitous drops in $\underline{n}$ for both species at the positions of the moons Ganymede at 15.1 R_J, Europa at 9.47 R_J, and Io at 5.95 R_J. Jupiter's innermost moon, Amalthea at 2.55 R_J, has a diameter of only 200 km and is too small to intercept substantial flux.

These results are for particles which mirror at magnetic latitudes greater than 10^o. Due to the 10-degree tilt of Jupiter's magnetic dipole with respect to its rotation axis, trapped particles which remain very close to the magnetic equator will have a much lower probability of impacting any of the inner satellites. Thus the fluxes of particles which mirror at magnetic latitudes less than 10^o are significantly greater than the high-latitude fluxes (2).

Fig. 1 is the result of solving for each species a steady-state transport equation which contains the essential physics of particle diffusion in Jupiter's inner magnetosphere. For electrons this transport equation has the form

$$\text{(Source injection)} + \text{(Radial diffusion)} - \text{(Energy degradation)} - \text{(Satellite absorption)} = 0 \qquad (1)$$

Because of the energy degradation term, n_e is a function of both R and energy E. (We, however, use the theoretically convenient variables R and the particle's magnetic moment μ.)

Both electrons and protons in our model come from the solar wind. They are presumably injected at Jupiter's magnetopause, estimated to be 50 R_J out from the center of the planet, and move radially toward the surface of the planet by processes which conserve the value of μ for each particle. The interesting physics for us occurs inside 20 R_J. We simulate all that occurs outside this region by putting the source in Eq. (1) at 35 R_J. The source is sufficiently beyond 20 R_J that our results are insensitive to its position. The source is assumed to be monoenergetic with the magnetic moment μ_o = 770 Mev/gauss. The electron density in Fig. 1 is for this same value of μ.

Once injected at $35 R_J$, trapped particles move radially toward (and away from) Jupiter's surface by a diffusion process. There is a general consensus (3-7) that in this region of Jupiter's magnetosphere there is a rapid radial diffusion which may result from the interaction of the electrons and protons with electric field fluctuations generated by an atmospheric-ionospheric dynamo. The rate of radial diffusion should be approximately the same for protons and electrons. By fitting the observed radial distribution of Jupiter's decimeter radio emission (8) to a model of trapped electrons emitting synchrotron radiation, we have estimated (5) the electron radial diffusion coefficient to be $\underline{D} = (1.7 \pm 0.5) \times 10^{-9} (R/R_J)^{1.95 \pm 0.5} R_J^2/\mathrm{sec}$. (The best-fit value μ_o = 770 Mev/gauss also comes from this analysis.) We assume that this value of $\underline{D}$ can be extrapolated out to 20 R_J, although the radio emission is insignificant beyond 4 R_J.

The energy degradation term in Eq. 1 is due to synchrotron radiation emission, which is effective only in the region 1 - 4 R_J. At 1.85 R_J, the center of the synchrotron emission region, a 10-Mev electron loses half its energy via synchrotron radiation in approximately six months. Because of their much greater mass, protons with comparable energies do not emit synchrotron radiation and consequently there is no such energy degradation term in the proton equation.

The remaining factor in Eq. 1 represents particle absorption by the satellites Amalthea, Io, Europa, and Ganymede. We assume that these four moons sweep up in snowplow fashion any particles which lie in their paths (2). The electrical conductivity of these satellites is taken to be sufficiently low that they do not distort the electromagnetic fields in Jupiter's magnetosphere and thus trapped particles cannot slip around and past the satellites.

Fig. 2 shows the trajectory of Pioneer 10 in magnetic coordinates. At perijove, 0225 UT on 4 December 1973, the spacecraft will be 2.86 R_J from the center of the planet at a magnetic latitude of 7.6°. The period of greatest danger to the spacecraft appears to lie during the 5 hours just prior to perijove passage, when the spacecraft will be inside 7 R_J at magnetic latitudes from -9° to +8°. It is in this latitude region where the moons are least effective in absorbing radiation belt particles and where fluxes are expected to be the most intense. We have calculated the absorption effect as a function of magnetic latitude and averaged the reduction factor over this portion of the trajectory. The average fluxes should be about a factor of 100 less than they would be if there were no absorbing moons. This may be enough to prevent serious radiation damage to the spacecraft.

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References and Notes

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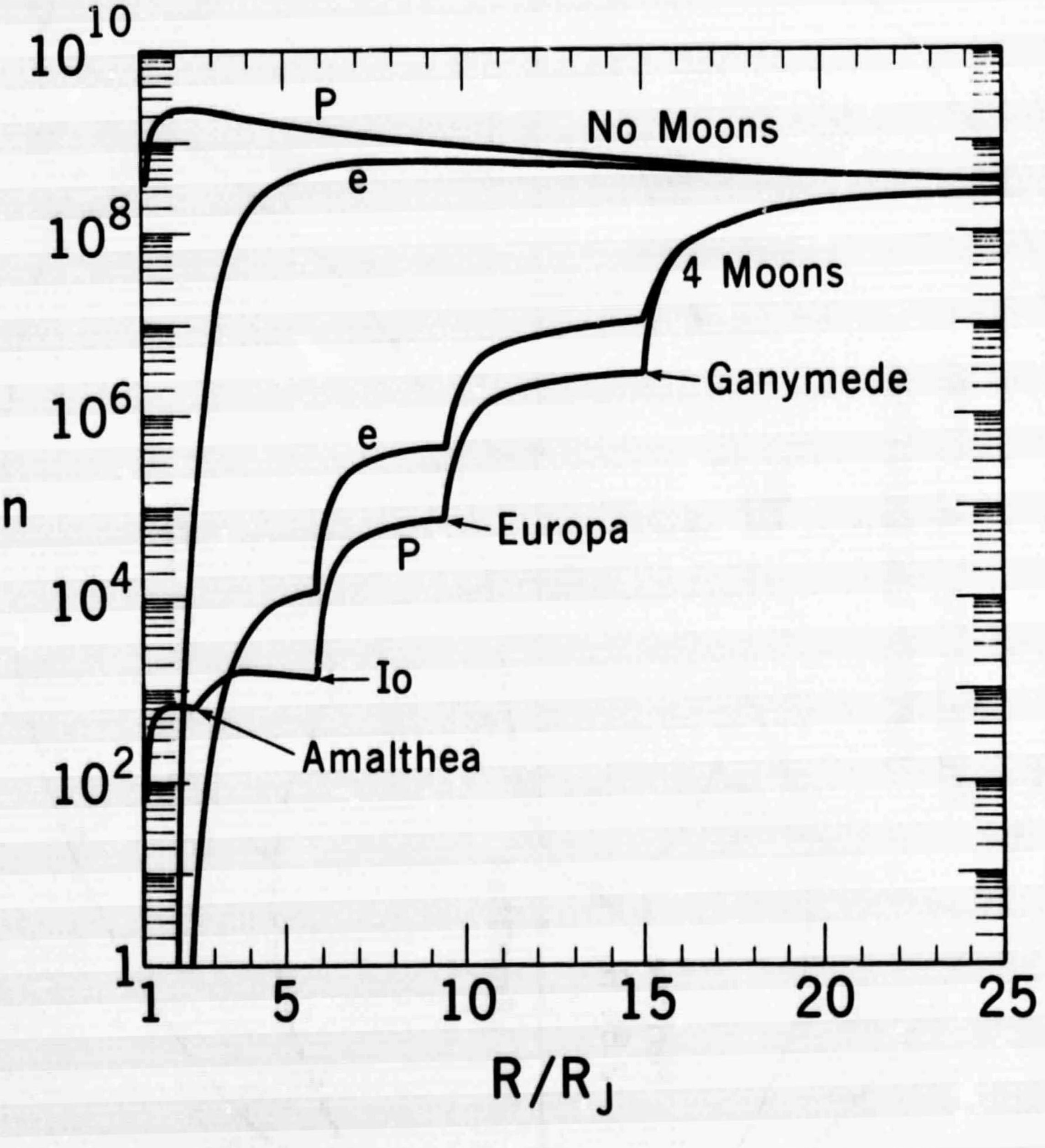
9. A more complete presentation of the technique and results outlined here is in preparation to be submitted to J. Geophys. Res.

Figure Captions

1. Calculated phase space densities of μ = 770 Mev/gauss electrons and protons with and without the wipe-out effect of the moons taken into account. The calculations with moons are for particles which mirror at latitudes greater than 10^{o}, where the wipe-out effect is maximized.
2. The trajectory of Pioneer 10 as a function of radius and magnetic latitude. The satellites Amalthea, Io, and Europa are shown as points in the equatorial plane, although each oscillates in magnetic latitude with amplitude 10^{o}.



10^{10}
10^8
10^6
10^4
10^2
1
n
P
No Moons
e
4 Moons
Ganymede
e
Europa
P
Io
Amalthea
1
5
10
15
20
25
R/R_J

Figure 1

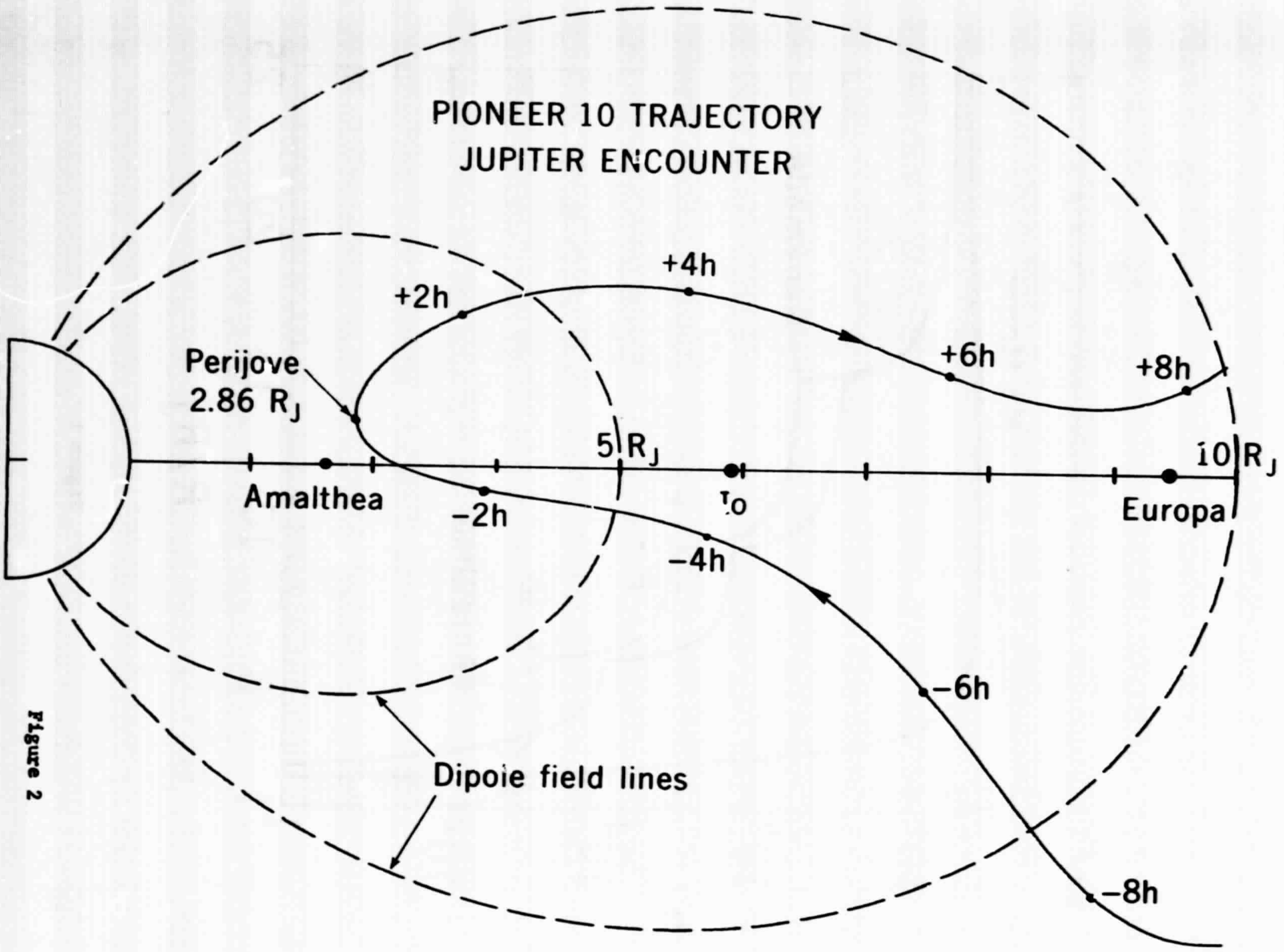


Figure 2

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