Reports

Pioneer 10 Jovian Encounter: Radiation Dose and Implications for Biological Lethality

Abstract. *In its recent Jupiter flyby Pioneer 10 passed through a belt of intense particulate radiation. The radiation dose on the outer surface of the spacecraft was at least 4.9×10^5 rads from electrons plus 2.9×10^6 rads from protons, sufficient to cause significant microbial decontamination. The radiation dose inside Pioneer 10, approximately 2.8×10^5 to 4.9×10^5 rads, was less likely to cause microbial decontamination but would be lethal to man and to most multicellular biological organisms.*

The planet Jupiter, like the planet Earth, is circled by a roughly toroid-shaped belt of trapped ionizing particles. This "trapped radiation belt" (TRB) or "Van Allen radiation belt" consists mainly of electrons and protons, with smaller fluxes of α and other particles. Prior to the Pioneer 10 Jupiter flyby, it had been estimated that Jupiter's TRB extended from 5 to 2 Jupiter radii (R_J), and that the maximum flux of 1- to 30-Mev electrons was, at most, 2.6×10^7 cm^{-2} sec^{-1} (*1*). The Pioneer 10 data, which will be discussed below, show that the TRB begins at 20 R_J and extends in at least to 2.8 R_J (*2*), and show a maximum flux of 3- to 20-Mev electrons of 5×10^8 cm^{-2} sec^{-1} (*3*). Clearly, the radiation levels surrounding Jupiter have been underestimated. Preliminary reports in the 25 January 1974 issue of *Science* concerned the charged particles encountered by Pioneer 10 during its recent Jupiter flyby. This report summarizes the particle fluences encountered by Pioneer 10 during its flight inbound from 108 R_J to periapsis (2.8 R_J) and outbound from periapsis to 105 R_J, estimates the radiation dose received as a result of this encounter, and considers the implications of such an exposure on the survival of biological materials.

There were 15 detectors for energetic electrons and protons onboard Pioneer 10, as listed in Table 1. Seven detectors (detectors A to G) counted electrons in the range from 0.41 to > 50 Mev, and eight detectors (detectors H to O) counted protons in the range from 0.44 to 150 Mev. The particle fluences encountered during various portions of the flight are given in Table 1. These fluences were calculated by numerical integration of the flux data given in the *Science* reports (*3–6*). Some of the detectors (A, C, D, I, and J) apparently saturated when the spacecraft was within the TRB (20 $R_J \rightarrow$ periapsis $\rightarrow$ 20 R_J). The fluences listed for these detectors are minimum estimates based on the assumption that during the saturated period the flux was at least equal to the last measurable inbound flux.

To calculate absorbed radiation dose, electron and proton fluences were first determined for the various energy ranges which could be distinguished by the detectors on Pioneer 10. Since there were several overlaps in the energy ranges of the various detectors, it was frequently necessary to subtract appropriate detector fluences to obtain an approximate energy spectrum (for example, the proton fluence in the 3.3- to 5.6-Mev range was obtained by subtracting the fluence for detector L, counting 5.6- to 21-Mev protons, from the fluence for detector K, counting 3.3- to 21-Mev protons). In cases where the degree of overlap could not be determined (for example, between detector D, counting 6- to 30-Mev electrons, and detector F, counting $\geqq$21-Mev electrons), minimum estimates of fluence were used. The absorbed radiation dose in rads for biological materials was then calculated for each energy range as the product of particle fluence and the linear energy transfer rate (LET) (*7*) in water. Where LET varied sig-

Table 1. Energy ranges and estimated fluences (per square centimeter) for Pioneer 10 energetic particle detectors for the jovian inbound and outbound passage (108 $R_J \rightarrow$ periapsis $\rightarrow$ 105 R_J).

Detector symbol	Energy range (Mev)	Inbound		Outbound					Reference
		108 R_J to 20 R_J	20 R_J to 2.8 R_J	2.8 R_J to 20 R_J	20 R_J to 35 R_J	20 R_J to 80 R_J	35 R_J to 80 R_J	80 R_J to 105 R_J	
				Electron fluences					
A	0.41–1.0	7.8×10^{10}	6.1×10^{11}*	3.9×10^{11}*	2.4×10^{9}		1.9×10^{9}		(*5*)
B	>3		7.9×10^{12}	6.1×10^{12}					(*3*)
C	>6	3.0×10^{9}	6.1×10^{9}*	7.7×10^{10}*	9.5×10^{7}		5.3×10^{7}		(*5*)
D	6–30	3.5×10^{9}	2.0×10^{11}*	1.7×10^{10}*	2.5×10^{7}		3.3×10^{7}	1.8×10^{7}	(*3*)
E	>20		5.3×10^{12}	3.8×10^{12}					(*6*)
F	≧21	1.1×10^{8}	1.9×10^{11}	1.1×10^{11}	4.1×10^{6}				(*4*)
G	>50		1.4×10^{11}	5.7×10^{10}					(*6*)
				Proton fluences					
H	0.5–1.8	4.0×10^{10}	2.5×10^{11}	2.3×10^{11}		1.0×10^{10}		2.6×10^{9}	(*3*)
I	0.44–2.0	1.1×10^{10}	6.1×10^{10}*	1.0×10^{11}*		7.6×10^{8}			(*5*)
J	>1.23	1.5×10^{9}	3.3×10^{11}*	2.1×10^{11}*		6.1×10^{7}			(*5*)
K	3.3–21	1.3×10^{8}	1.0×10^{11}	6.8×10^{10}		5.8×10^{6}			(*5*)
L	5.6–21	1.3×10^{7}	3.1×10^{10}	3.4×10^{10}		1.0×10^{6}			(*5*)
M	16.2–21	3.9×10^{5}	8.9×10^{9}	6.8×10^{8}		3.5×10^{4}			(*5*)
N	>30		1.2×10^{10}	8.3×10^{9}					(*3*)
O	70–150		3.0×10^{8}	1.3×10^{8}					(*6*)

* Detector apparently saturated.

nificantly over a given energy range, an intermediate value was used.

Table 2. Estimated radiation dose from Jupiter's radiation belts ($20\ R_J \rightarrow$ periapsis $\rightarrow 20\ R_J$).

Energy class (Mev)	LET (Mev cm^2 g^{-1})	Fluence (cm^{-2})	Surface dose (rad)	Range in aluminum (cm)
		Electron dose		
0.41–1.0 (A)	2.5	1.0×10^{12}	3.9×10^4	0.04 –0.16
3–20 (B–E)	2	5.0×10^{12}	1.6×10^5	0.54 –3.4
20–21 (E–F)*	2	8.8×10^{12}	2.8×10^5	3.4
21–50 (F–G)	2	1.0×10^{11}	3.3×10^3	3.4 –7.3
> 50 (G)	2	2.0×10^{11}	6.3×10^3	> 7.3
Total			4.9×10^5	
		Proton dose		
0.5–1.8 (H)	3×10^2	4.8×10^{11}	2.3×10^6	0.0003–0.002
3.3–5.6 (K–L)	1.3×10^2	1.1×10^{11}	2.2×10^5	0.006–0.016
5.6–16.2 (L–M)	6×10^1	5.5×10^{10}	5.7×10^4	0.016–0.14
16.2–21 (M)	2×10^1	9.6×10^9	3.0×10^3	0.14 –0.2
30–70 (N–O)	1.4×10^1	2.0×10^{10}	4.5×10^3	0.3 –1.6
70–150 (O)	8×10^0	4.3×10^8	5.5×10^1	1.6 –5.7
Total			2.6×10^6	

* Because of uncertainty in the absolute calibration of the various detectors, the designated energy ranges are only approximate; the "20- to 21-Mev" fluence probably represents a considerably broader energy range.

Table 2 shows the calculation of energy spectra and radiation dose for electrons and protons within Jupiter's TRB ($20\ R_J \rightarrow$ periapsis $\rightarrow 20\ R_J$). The estimated surface electron dose was 4.9×10^5 rads. We estimate that the electrons detected during the flight inbound from 108 R_J to 20 R_J and outbound from 20 R_J to 105 R_J added 3.4×10^3 rads, for a total surface electron dose of 4.9×10^5 rads. The estimated surface proton dose within the radiation belt was 2.6×10^6 rads. We estimate that protons in the $108\ R_J \rightarrow 20\ R_J$ and $20\ R_J \rightarrow 105\ R_J$ portions of the flight added 2.5×10^5 rads for a total surface proton dose of 2.9×10^6 rads.

Within the spacecraft the radiation dose was considerably reduced since the spacecraft skin absorbed some of the electrons and most of the protons. A "typical" spacecraft skin, a layer of aluminum approximately 0.25 cm thick, would absorb the 0.41- to 1.0-Mev electrons and all but the > 30-Mev protons. Thus, immediately behind the skin the electron dose would be 4.5×10^5 rads and the proton dose would be 4.5×10^4 rads. Some areas within the spacecraft would be further shielded by interior structures. We estimate that the maximum shielding would be approximately 1 cm of aluminum, and that the "> 20-Mev" electrons (detector E) would penetrate at least that thickness of shielding. Thus, we estimate that all interior areas of Pioneer 10 received a radiation dose of at least 2.8×10^5 rads.

The above calculations represent minimum dose estimates, since we limited ourselves to particles detected by the instruments onboard Pioneer 10. In this we excluded particles for which there were no detectors (for example, electrons with energies below 0.41 Mev or between 1 and 3 Mev) or for which the detectors saturated (for example, protons with energies between 1.8 and 3.3 Mev). These excluded particles would contribute heavily to the surface dose. Moreover, the production of secondary particles and x-rays, which have been neglected in our calculations, would add to the dose calculated for primary particles.

Investigators at the Jet Propulsion Laboratory (JPL), Pasadena, California, have been conducting research to determine the effect of planetary TRB's on the survival of microorganisms associated with nonsterile spacecraft (*8, 9*). Bacterial subpopulations from the Mariner Mars 1971 spacecraft [nine spore-forming isolates and three nonspore-forming isolates (vegetative bacterial cells)] were exposed to 2- to 25-Mev electrons (*8*) and to 2-Mev protons (*9*). A 300-krad dose of electrons resulted in a mean survival fraction of 0.05 for the spore-formers and 0.007 for the nonspore-formers; a dose of 450 krad of electrons resulted in a survival fraction of 0.01 for spore-formers and 0.003 for nonspore-formers (*8*). A dose of 2.7 Mrad of protons yielded a survival fraction of 0.1 for spore-formers and approximately 0.0001 for nonspore-formers (*9*).

On the basis of our calculated surface dose (490-krad electrons plus 2.7-Mrad protons) and the JPL findings, we would predict a survival fraction of less than 0.001 for spore-formers on the surface and a survival fraction of less than approximately 3×10^{-7} for nonspore-formers on the surface. Since the actual surface dose was probably considerably higher than our calculated dose, the survival of spore-formers was probably well below 0.001 and the nonspore-formers were probably virtually eliminated. Thus, the outer surface of Pioneer 10 was significantly decontaminated by the radiation exposure.

We estimate that within the spacecraft the total dose was 280 to 500 krad, due mainly to electrons. This dose would have resulted in a spore survival of approximately 0.05 to 0.01. Thus, a significant fraction of whatever spore-formers were present would have survived the jovian radiation dose within Pioneer 10. Nonspore-formers would have had a survival fraction of approximately 0.003 to 0.007. For almost all "higher" forms of life—such as seeds, plants, algae, worms, insects, and others—the radiation dose inside Pioneer 10 would have been supralethal. For man and other mammals the interior dose far exceeded the lethal level. Thus, Jupiter's radiation belts pose an extreme hazard to any manned mission passing through them. However, were a space vehicle to approach Jupiter along the polar axis, the radiation belts would not be encountered and the radiation hazard might be considerably less.

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