cally neutral. Finally, the proton radial diffusion model is completed by assuming that the only proton loss is caused by absorption at the surface of Jupiter (*7*). The total omnidirectional flux for the predicted proton radiation belt model is shown in Fig. 2, where again contours of constant flux are plotted against magnetic latitude and distance from the center of Jupiter. The maximum predicted proton flux of 1.8×10^{10} cm^{-2} sec^{-1} occurs at 1.3 R_J from the center, where the characteristic energy is 340 Mev. By comparison with the electrons, the protons have a maximum flux closer to Jupiter and much sharper in spatial distribution.

These predictions are in basic agreement with other recent work on the subject (*8*). However, both the proton and electron predictions represent fluxes that are more than 100 times the fluxes of the nominal models used in the design of Pioneer 10 (*9*). This indicates that there is a significant chance of radiation damage to the spacecraft. For the measurements that are obtained by Pioneer 10 it will be very interesting to compare the predictions presented here with the actual observations of Jupiter's radiation belts (*10*).

KENT G. STANSBERRY
Aerospace Corporation,
El Segundo, California 90245

R. STEPHEN WHITE
Department of Physics,
University of California,
Riverside 92502

References and Notes

1. F. D. Drake and S. Hvatum, *Astron. J.* **64**, 329 (1959).
2. N. Brice and T. R. McDonough, *Icaras* **18**, 206 (1973).
3. T. A. Farley and M. Walt, *J. Geophys. Res.* **76**, 8223 (1971).
4. D. B. Chang and L. Davis, Jr., *Astrophys. J.* **136**, 567 (1962).
5. J. A. Roberts, *J. Res. Nat. Bur. Stand.* **69**, 1543 (1965).
6. G. L. Berge, *Astrophys. J.* **146**, 767 (1966); N. J. B. A. Branson, *Mon. Not. Roy. Astron. Soc.* **139**, 155 (1968).
7. Synchrotron radiation is caused by the charged particle acclerations in a magnetic field. Because of their greater mass, protons are accelerated much less than electrons and hence are influenced much less by synchrotron radiation effects. The combination of magnetic field strength and proton kinetic energy at Jupiter means that radiation from protons is down by more than a factor of 10^6 compared to electrons.
8. F. V. Coroniti, C. F. Kennel, R. M. Thorne, *Astrophys. J.*, in press.
9. N. Divine, *Proceedings of the Jupiter Radiation Belt Workshop*, A. J. Beck, Ed. (Technical memorandum 33-543, Jet Propulsion Laboratory, Pasadena, California, 1972), p. 527.
10. A more complete presentation of the technique and results outlined here is in preparation by K.G.S. and R.S.W.
11. Supported by an advanced study fellowship from the Aerospace Corporation, El Segundo, California, Themis contract N00014-69-A-0200-5004 and by NASA grant NGR-05-008-022.

19 October 1973

Jupiter's Radiation Belts: Can Pioneer 10 Survive?

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 Jupiter radii (1 $R_J \cong$ 70,000 km). This is a phase space density n, which is linearly proportional to particle flux F, so that sharp decreases in n imply proportionally sharp decreases in F. Figure 1 has one overall arbitrary normalization factor, and only the relative variations of the proton and electron densities n_p and n_e with radius R are significant. Note the precipitous drops in 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,

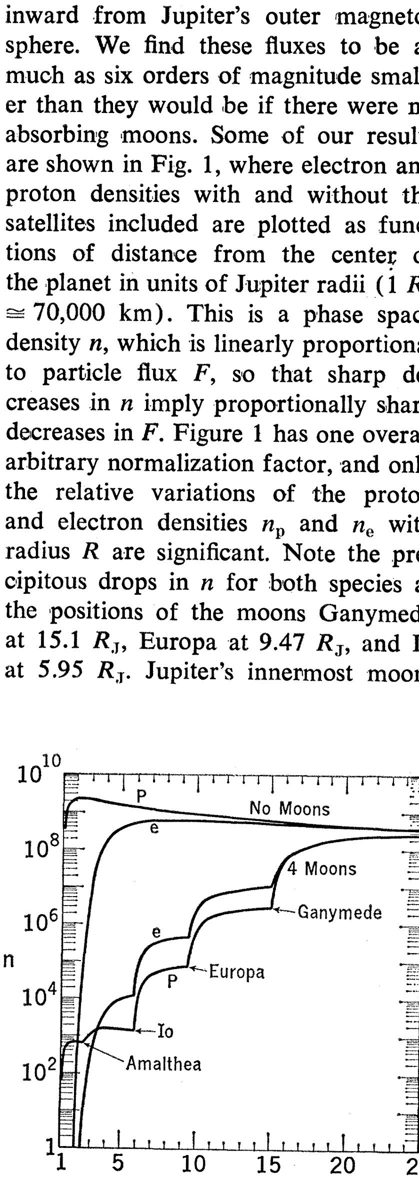

Fig. 1. Calculated phase space densities of $\mu = 770$ Mev/gauss electrons and protons with and without inclusion of the wipe-out effect of the moons. The calculations with moons are for particles which mirror at latitudes greater than 10°, where the wipe-out effect is maximized.

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°. Due to the 10° 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° are significantly greater than the high-latitude fluxes (*2*).

Figure 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 $\mu_0 = 770$ 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, 4*) that in this region of Jupiter's magnetosphere there is a rapid radial diffusion which may result from the

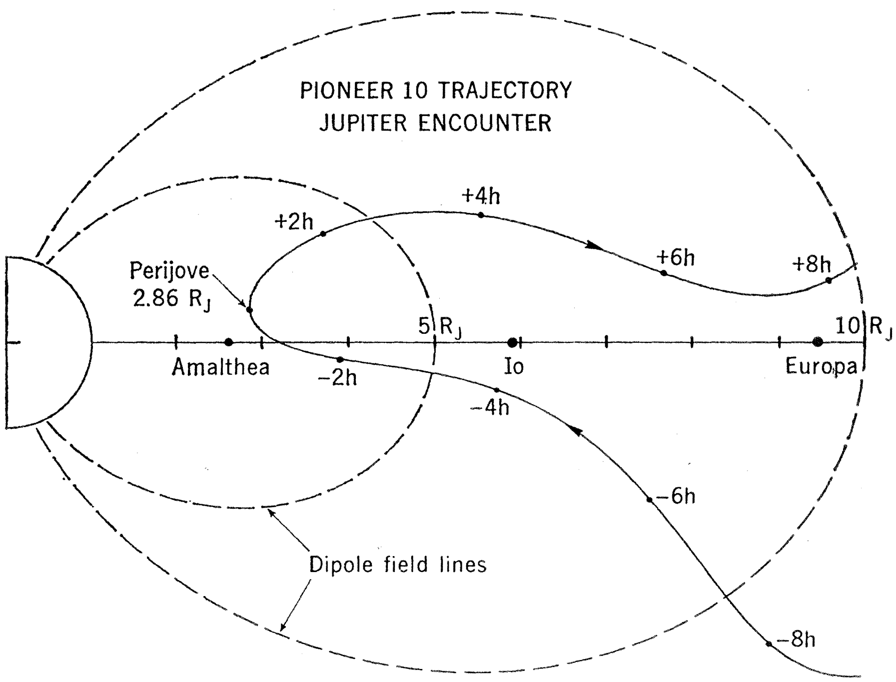

Fig. 2. Trajectory of Pioneer 10 as a function of radius and magnetic latitude. The satellites Amalthea, Io, and Europa are shown as points in the equatorial plane, although each oscillates in magnetic latitude with amplitude 10°. Times in hours (h) before (−) and after (+) perijove are indicated along the trajectory.

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 (*5*) to a model of trapped electrons emitting synchrotron radiation, we have estimated (*4*) the electron radial diffusion coefficient to be $D = (1.7 \pm 0.5) \times 10^{-9} (R/R_J)^{1.95 \pm 0.5} R_J^2$/sec. (The best-fit value $\mu_0 = 770$ Mev/gauss also comes from this analysis.) We assume that this value of 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 to 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 6 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.

Figure 2 shows the trajectory of Pioneer 10 in magnetic coordinates. At perijove (the position of closest approach to Jupiter), 0225 U.T. 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 before perijove passage, when the spacecraft will be inside 7 R_J at magnetic latitudes from −9° to +8°. This is the 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 (*6*).

W. N. Hess
Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Boulder, Colorado 80302

T. J. Birmingham, G. D. Mead
Laboratory for Space Physics, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771

References and Notes

1. See, for example, various articles in *Proceedings of the Jupiter Radiation Belt Workshop*, A. J. Beck, Ed. (Technical Memorandum 33-543, Jet Propulsion Laboratory, Pasadena, Calif., 1972).
2. G. D. Mead and W. N. Hess, *J. Geophys. Res.* **78**, 2793 (1973).
3. N. Brice and T. R. McDonough, *Icarus* **18**, 206 (1973); S. A. Jacques and L. Davis, Jr., unpublished manuscript; F. V. Coroniti, *Astrophys. J.*, in press; K. G. Stansberry and R. S. White, *J. Geophys. Res.*, in press.
4. T. Birmingham, W. Hess, T. Northrop, R. Baxter, M. Lojko, *J. Geophys. Res.*, in press.
5. G. L. Berge, *Astrophys. J.* **146**, 767 (1966).
6. A more complete presentation of the technique and results outlined here is in preparation by W.N.H., T.J.B., and G.D.M.

9 November 1973

Hyperactivity and Brain Catecholamines in Lead-Exposed Developing Rats

Abstract. *Newborn rats that suckled mothers eating a diet containing 4 percent lead carbonate display hyperactivity, aggressiveness, and excessive stereotyped behavior starting at 4 weeks of age. There is an eightfold increase in the concentration of lead in brain, no change in norepinephrine, but a 20 percent decrease in dopamine relative to coetaneous controls. This suggests a relationship between central nervous system dysfunction due to lead and dopamine metabolism in brain.*

The nervous system is very sensitive to the toxic effects of lead, and it is the young who are particularly susceptible to cerebral dysfunction produced by lead (*1*). Although the histopathological findings of lead encephalopathy are well documented (*2*), practically nothing is known about the biochemical changes in brain following acute lead intoxication or chronic low-level exposures to lead during early developmental years. An experimental model with morphological alterations closely resembling those occurring in humans with lead toxicity has been described by Pentschew and Garro (*3*). This model utilizes the suckling rat and in some ways is analogous to pica seen in clinical