Radiation Belts of Jupiter

Abstract. *Predictions of Jupiter's electron and proton radiation belts are based mainly on decimeter observations of 1966 and 1968. Extensive calculations modeling radial diffusion of particles inward from the solar wind and electron synchrotron radiation are used to relate the predictions and observations.*

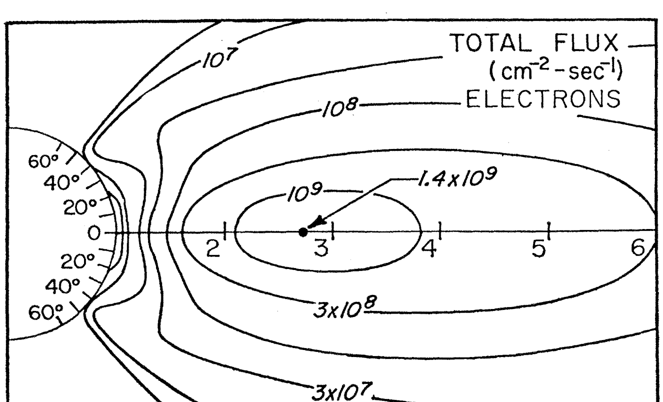
The radiation belts of the planet Jupiter have been of considerable interest ever since synchrotron radiation from energetic electrons was suggested as the source of Jupiter's decimetric radio wave radiation (*1*). Recently, this interest has increased because the space probe Pioneer 10 will encounter Jupiter's radiation belts in December 1973. Before the arrival of Pioneer 10 there is a need to understand the space environment near Jupiter theoretically and to predict the fluxes of protons and electrons trapped there because of the possible radiation damage to the spacecraft. The results of such a theoretical study of the radiation belts of Jupiter are presented below.

The model of the electron radiation belt is based on the assumption that electrons from the solar wind are transported into the region near Jupiter by radial diffusion. The diffusion is driven by electric fields caused by an upper atmospheric dynamo in Jupiter's ionosphere (*2*). The loss mechanisms that are assumed to apply to the trapped electrons are (i) absorption at the planetary surface; (ii) synchrotron radiation energy loss; and (iii) an unexplained loss mechanism. The unexplained loss is required before agreement is obtained between the characteristics of the predicted electron model and the radio wave observations. This loss must be strongest within ½ to 1 Jupiter radius from the surface, and hence is not associated with loss caused by collision of particles with Jupiter's natural satellites. The basic properties of the predicted electron radiation belt are calculated from the radial diffusion formulation in a manner similar to that applied to the earth's radiation belts (*3*).

Since radial diffusion does not alter the magnetic moment associated with the electron cyclotron motion, the electrons are accelerated to relativistic energies as they move into the strong magnetic field near the planet. At these high energies the electrons emit synchrotron radiation, which is the decimeter radiation observed on the earth. A generalization of a previous formulation of Jupiter's synchrotron characteristics (*4*) is used to compare the earth-based radio wave observations with the predictions based on the electron radiation belt model. The magnetic field is modeled as a planet-centered dipole with an equatorial surface intensity of 11.5 gauss. Comparisons are made between the predicted and observed total flux densities in the decimeter wavelength range (*5*), radio wave distribution as a function of distance from Jupiter (*6*), and degree of polarization of the radio waves. The magnitude of the predicted radiation belt electron flux is obtained by equating the calculated radio wave flux density at a wavelength of 28 cm to the observed 6.7×10^{-26} watt m^{-2} $hertz^{-1}$, at the standard distance of 4.04 A.U. from the earth.

The total omnidirectional flux for the predicted electron radiation belt model is shown in Fig. 1, where contours of constant flux are plotted against magnetic latitude and distance from the center of Jupiter. The maximum predicted electron flux of 1.4×10^9 electrons per square centimeter per second occurs at 2.7 R_J (Jupiter radii) from the planetary center where the characteristic electron energy is 7 Mev. The predicted electron flux is greater than 10^9 cm^{-2} sec^{-1} throughout the region from 2.1 to 3.8 R_J from the center, where the characteristic energies are 11 and 4 Mev, respectively.

There is no direct evidence to indicate the presence of a proton radiation belt at Jupiter. However, analogy with the earth's radiation belts suggests that protons are present at Jupiter. Thus, a proton radiation belt at Jupiter is predicted, with the proton characteristics derived from the electron characteristics. The proton source is also assumed to be the solar wind, from which the protons undergo radial diffusion inward like the electrons. The magnitude of the predicted total flux in the proton radiation belt is found by assuming that the same density of protons as electrons is present at the outer boundary of the radiation belt. In other words, since the solar wind is electrically neutral, it is assumed that the region of the radiation belts near the solar wind is also electri-



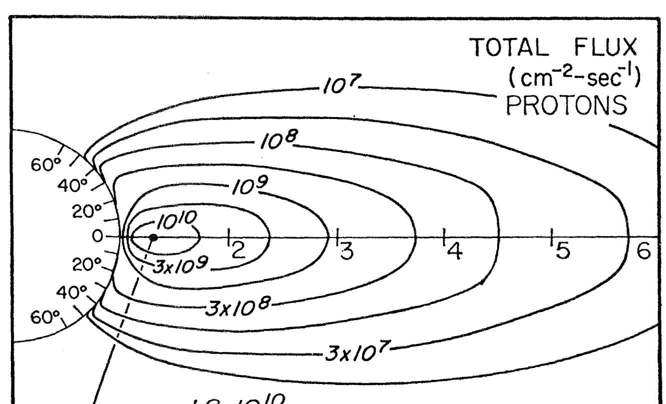


Fig. 1 (left). Predicted total omnidirectional flux in the electron radiation belt of Jupiter. Contours of constant flux are shown with magnetic latitude (degrees) and distance from the center of Jupiter (Jupiter radii). The maximum predicted electron flux of 1.4×10^9 electrons per square centimeter per second occurs at 2.7 R_J from the planetary center, where the characteristic energy is 7 Mev. Fig. 2 (right). Predicted total omnidirectional flux in the proton radiation belt of Jupiter. The maximum predicted proton flux of 1.8×10^{10} protons per square centimeter per second occurs at 1.3 R_J from the planetary center, where the characteristic energy is 340 Mev.

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).

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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.
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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, Amalthea at 2.55 R_J, has a diameter of only 200 km and is too small to intercept substantial flux.

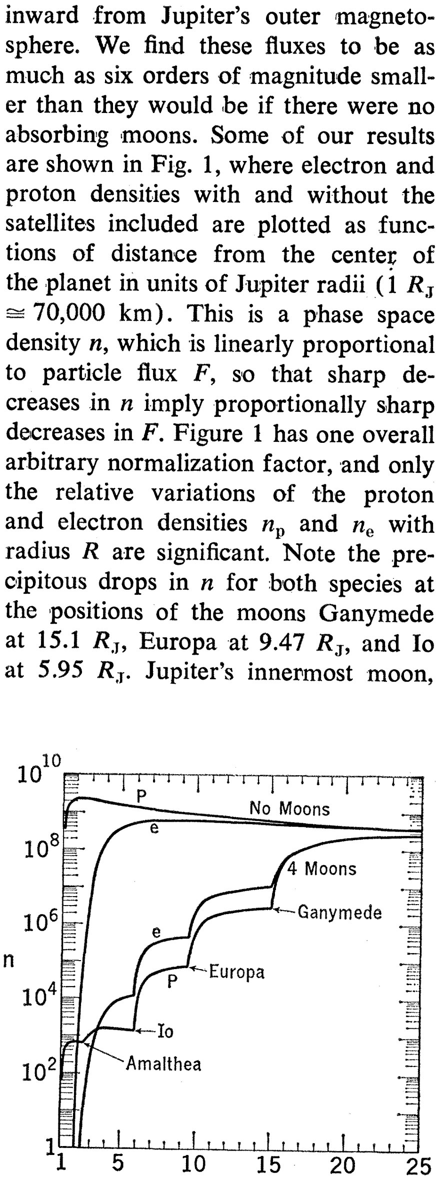

Fig. 1. Calculated phase space densities of $\mu = 770$ Mev/gauss electrons and protons with and without inclusion of the wipe-out effect of the moons. The calculations with moons are for particles which mirror at latitudes greater than 10°, where the wipe-out effect is maximized.

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