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Impact of Saturn Ring Particles on Pioneer 11

Abstract. *The particle flux measured by the meteoroid detectors on Pioneer 11 increased greatly while the spacecraft was near the rings of Saturn. The data suggest that the particles were associated with the rings and were not interplanetary meteoroids concentrated near the planet by gravitational focusing. The data also suggest that the E ring may be 1800 kilometers thick with an optical thickness greater than 10^{-8}.*

The meteoroid detection instrument on Pioneer 11, which was designed to determine the concentration of meteoroids with masses in excess of 10^{-8} g in the asteroid belt (*1*), detected several particles near the rings of Saturn.

The instrument has 234 detectors, consisting of pressurized cells with stainless steel walls 50 μm thick, distributed between two independent data channels. As the gas leaks from a cell after its penetration by a particle, the internal pressure passes through a limited region in which a pressure monitoring device produces a signal that causes the counter for that channel to advance and then to become inhibited for 77 minutes to allow time for all the gas to leak out of the cell (*2*). Particles that penetrate other cells on that channel while the counter is inhibited are not detected. This 77-minute dead time did not have a significant effect on the data obtained in interplanetary space because the mean time between impacts was about 27 days. However, this feature of the instrument severely limited its ability to measure the magnitude of the particle population near Saturn.

In most cases, all of the gas will escape in less than 2 seconds (*2*). There is, however, a small chance that such an extremely small hole might be produced by a penetration near threshold that the cell would still contain enough gas after the 77-minute inhibitory period to trip the counter again and start another inhibitory period.

The counters indicated that 87 cells were punctured prior to the encounter with Saturn, leaving 147 active cells as the spacecraft approached the planet.

At least four particles penetrated the detectors in the 4.5-hour period around periapsis, at least two on each data channel. The time and range of the spacecraft when the counters advanced are shown in Fig. 1. The reason for the uncertainty in the number of particles detected is that the third count on channel 0 occurred 72 to 82 minutes after the second count. If the count occurred at 77 minutes it could have been the result of a slowly leaking cell, and only four particles would then have been detected. If the count occurred between 77 minutes and 82 minutes, then five particles were detected. In either case, the counters were inhibited for approximately 70 percent of the 4.5-hour period so that other impacts probably occurred but were not detected. The penetration flux near Saturn was at least 1000 times that in interplanetary space at 9.4 AU.

The meteoroid flux measured by a penetration detector is expected to increase as a spacecraft approaches a planet because the gravitational field of the planet accelerates and focuses the interplanetary meteoroids. The data obtained near Jupiter by Pioneer 10 and Pioneer 11 are in agreement with gravitational focusing theory (*3*). The data obtained near Saturn, however, cannot be explained by gravitational focusing. It is not the total number of particles detected near Saturn, but rather the distribution with respect to radial distance that is inconsistent with gravitational focusing. All impacts occurred between 1.36 and 3.1 Saturn radii (R_S); no impacts occurred between 3.1 and 425 R_s. Gravitationally focused meteoroids should have produced twice as many penetrations between 3.1 and 50 R_s as between 1.36 and 3.1 R_s, if the mass distribution index of the meteoroids is -0.34 [as the Pioneer 10 and Pioneer 11 data suggest for the range between 10^{-8} and 10^{-9} g (*3*)]. Therefore, it is unlikely that any of the particles detected near Saturn were meteoroids. They were probably particles associated with the rings, that is, ring particles themselves or particles ejected from the rings because of collisions.

The two particles detected just before the first crossing of the ring plane could be E ring particles. These particles were detected 900 km above the ring plane (0.28°N latitude), which suggests that the E ring may be 1800 km thick. Particles could remain in inclined orbits for some time in this tenuous ring without colliding with other ring particles.

The time between these two impacts was 24 to 120 seconds. If it is assumed that this interval is representative of the mean time between the impacts of penetrating particles on the active cells in the E ring, and if it is further assumed that the size distribution of the E ring particles is meteoroidal (*4*), then the optical thickness of the E ring is calculated to be 1×10^{-8} to 5×10^{-8}. Of course, if the ring particles are not uniformly distributed throughout the 1800-km-thick ring, but are concentrated more heavily near the equatorial plane, the above optical thickness is a lower limit.

The calculated reduction in spacecraft speed due to the impact of particles during one passage through such a ring is

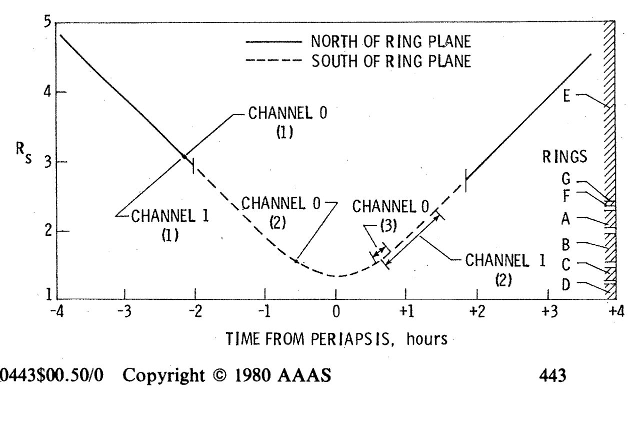

Fig. 1. The range of the Pioneer 11 spacecraft with respect to Saturn during encounter, showing the ranges and times at which particle impacts were detected by the meteoroid detection experiment.

10^{-5} to 10^{-6} m/sec. This effect cannot be resolved from the Pioneer 11 tracking data.

If the mean time between penetrating impacts was 24 to 120 seconds for the entire 1100-second passage through the E ring, only 9 to 46 of the 147 active cells would have been penetrated during the first crossing. That would leave many cells remaining for the flight under the rings and for the second E ring crossing. A similar loss of cells would be expected during the second E ring crossing. Unfortunately, both channels were inhibited for most, or all, of the second E ring crossing as the result of impacts that occurred while the spacecraft was beneath the bright rings of Saturn. These last impacts were probably from particles ejected from the optically thick rings as the result of collisions between ring particles or between meteoroids and ring particles.

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The Magnetic Field of Saturn: Pioneer 11 Observations

Abstract. *The intrinsic magnetic field of Saturn measured by the high-field fluxgate magnetometer is much weaker than expected. An analysis of preliminary data combined with the preliminary trajectory yield a model for the main planetary field which is a simple centered dipole of moment 0.20 ± 0.01 gauss-*R_S^3 *= 4.3 ± 0.2 × 10*^{28} *gauss-cm*^{3} *(1* R_S *= 1 Saturn radius = 60,000 km). The polarity is opposite that of Earth, and, surprisingly, the tilt is small, within 2° ± 1° of the rotation axis. The equatorial field intensity at the cloud tops is 0.2 gauss, and the polar intensity is 0.56 gauss. The unique moon Titan is expected to be located within the magnetosheath of Saturn or the interplanetary medium about 50 percent of the time because the average subsolar point distance to the magnetosphere is estimated to be 20* R_S, *the orbital distance to Titan.*

The Pioneer 11 high-field fluxgate magnetometer (FGM) experiment (*1*) consists of two biaxial fluxgate sensor assemblies and an associated electronics system; it is designed to measure fields up to 10 gauss along three orthogonal axes. This ultralightweight instrument, having low power requirements and a low bit rate, was selected for addition to the spacecraft only 3 months before launching in April 1973, in order to provide a higher upper range than that provided by the helium vector magnetometer, whose maximum measurable field is 1.4 gauss (*2*). Spin-synchronous, instantaneous vector measurements were obtained by the FGM at approximately 144-second intervals at Saturn, the sampling rate being determined by the spacecraft's spin period (7.7 seconds) and telemetry rate (0.2 bit per second) allocated to this experiment. The instrument response characteristics, coupled with the use of 10-bit analog-to-digital converters, yield a quantization step size of $\pm$ 600 γ (1 $\gamma = 10^{-5}$ gauss) for measured fields of intensity less than 2 gauss. The total weight of the instrument is 272 g, and the power required, 300 mW, was supplied by the cosmic-ray telescope experiment.

The results presented here are based on preliminary experiment data records and preliminary spacecraft trajectory and inertial attitude information. The clock or phase angle of the sun as seen from the spacecraft is extremely sensitive to errors in attitude determination since the spacecraft spin axis is directed toward Earth and at 10 AU the maximum cone or polar angle of the Sun is only ~ 2°. Thus, even a small error has a large effect on the computed orientation of the measured field relative to coordinates centered on the planet.

The magnetic field data are obtained in a quasi-inertial reference coordinate frame aligned with the ecliptic plane and are then transformed to a spherical coordinate system centered on Saturn and rotating with the planet; these data are combined with information on the spacecraft position to yield a measurement set with six variables. The adopted position of the rotation axis of Saturn is $\lambda_S = 78.81°$ and $\beta_S = 61.93°$, corresponding to ecliptic longitude and latitude in 1950.0 coordinates. The adopted rotation rate and reference meridian are those defined by the Jet Propulsion Laboratory (*3*) and correspond to a rotation period of 10 hours 14 minutes. In this coordinate system longitude increases eastward on the planet.

A total of 203 vector measurement sets were obtained during the close encounter phase on 1 September 1979, both inbound to and outbound from periapsis, corresponding to radial distances between 1.34 and 5 Saturn radii (R_S) (1 R_S = 60,000 km). During radio occultation, a reduced spacecraft data rate was in effect, so that this preliminary report includes no data from 1.34 to 2.29 R_S while outbound.

A projection of the spacecraft flyby trajectory onto the surface of the planet is shown in Fig. 1. Within 5 R_S, the latitude and longitude coverage extends only from 3.7° to −6.2° and 270° to 200°, respectively. To obtain a unique mathematical representation of the planetary field, observations over a closed surface containing the magnetic field sources are required. A flyby trajectory allows the acquisition of data only along the spacecraft path, and thus the mathematical models that can be derived from the observations are not unique. The Pioneer 11 encounter trajectory, with its limited coverage, provides a restricted sampling of the planetary field and imposes restrictions on the complexity of physically meaningful mathematical models that can be used to fit the observations. In general, this limitation is expressed in terms of the sensitivity of the problem to the propagation and amplification of errors and is quantitatively expressed by the condition number of the matrix associated with a least-squares fitting procedure (*4*).

The magnetic field, B, in a region containing no sources ($\nabla \times B = 0$) can be expressed as the gradient of a scalar potential V, which represents the contributions of sources internal and external to the region of interest. It is customary to express the potential in terms of spherical harmonics as

$$V = V^e + V^i = a \sum_{n=1}^{\infty} \{(r/a)^n T_n^e + (a/r)^{n+1} T_n^i\}$$

where r is the distance from Saturn's center, a is Saturn's radius, and the $T_n^{i,e}$ are given by

$$T_n^i = \sum_{m=0}^{n} P_n^m (\cos\theta) \times [g_n^m \cos m\phi + h_n^m \sin m\phi]$$

and

$$T_n^e = \sum_{m=0}^{n} P_n^m (\cos\theta) \times [G_n^m \cos m\phi + H_n^m \sin m\phi]$$