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PIONEER 11's ENCOUNTER WITH JUPITER AND MISSION TO SATURN

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16. Abstract

Pioneer 11, benefiting from Pioneer 10's first cautious exploration of Jupiter's environment, enlarged that survey of Jupiter and has become man's first space mission to Saturn. At one-third the altitude reached one year earlier, the December 3, 1974 flyby encountered high-energy proton intensities one to two orders of magnitude greater than that previously encountered and demonstrated a plateau in maximum electron intensity. Passing Jupiter in a spiral trajectory that was steeply inclined to the ecliptic and opposite to the planet's rotation, Pioneer 11 substantially diversified the survey of the magnetosphere and scans of cloud characteristics. The spacecraft and all of its planetary observation instruments survived encounter with Jupiter, and its power supply offers hope for full capability at the new mission objective in 1979, Saturn.

Present plans for Pioneer 11's approach to Saturn are described. A flyby somewhat parallel to the ring plane is being proposed as an interim target, with a future option held for a possible high risk (or suicide) plunge through the nearly transparent space between Saturn and its rings.

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MISSION

Objectives

Pioneer 11 was launched in April 1973, to insure achievement of the goals set for its twin Pioneer 10. Preliminary exploration of interplanetary space, the asteriod belt, and the environment of Jupiter were completed by Pioneer 10 at Jupiter eight months later. Ambitious expansion of the project's objectives were made possible by the Pioneer 10's nearly perfect performance. Pioneer 11 would arrive at Jupiter December 3, 1974, almost exactly one year after Pioneer 10.

Pioneer 11 was then redirected primarily to improve our understanding of Jupiter's radiation environment. Some of the most urgent questions concerned the temporal stability of the magnetosphere and its trapped radiation, latitudinal dependence and longitudinal independence of radiation intensity, and intensity of radiation inside the magnetic region traversed by Pioneer 10. These surveys of Jupiter's radiation are vital to scientific explanations and provide requisite design environments for spacecraft orbiters and probes on future missions. Open questions (which still persist) concern interactions of the magnetosphere with the solar wind and with satellites orbiting within it.

Consonant with improving the description of Jupiter's radiation, it was possible to extend the coverage and improve the spatial resolution in imaging, optical polarimetry, and infrared radiometry of the visible surface over that achieved with the first encounter. A low-altitude trajectory, highly inclined to Jupiter's equator, would be suitable for the above objectives and would improve definition of gravitational and magnetic fields as well.

Extension of Pioneer 11's flight to Saturn was agreed upon by authorizing officials in the spring of 1974, recognizing that the requisite trajectory near Jupiter was also among the best for probing deeper into Jupiter's environment. This possibility having long been recognized, Pioneer 11 was carefully targeted just after launch in April 1973, to preserve the option for a two-planet mission.

Trajectory

Flyby geometry relative to Jupiter specified by the Saturn objective presented a challenge to mission strategy and to navigational accuracy. Time of arrival was chosen such that penetration of Jupiter's magnetic equatorial plane (which is tilted 11° from the equator) would be as steep as possible to minimize radiation dosage. Exploiting the contrast in spin period between Jupiter's and the Earth's (9.9 hours and 24 hours) permitted selection of an encounter time which would result in simultaneous visibility from two Deep Space Network tracking stations, one in California and the other in Australia.

No adjustments after April 1974, were required to maintain confidence in our ability to reach Saturn with the remaining 90 meters/second maneuver capability. Any desired targeting around Saturn can now be achieved with practical velocity changes totalling less than 50 meters/second.

Encounter trajectory at Jupiter is shown in Figures 1 and 2 together with Pioneer 10's comparative trajectory. The planetary latitude of Pioneer 11's distant approach was about -5°; departure was near +30°. Trajectory comparisons of Pioneer 10 and 11 in terms of magnetic latitude and radius are shown relative to the interim magnetic field model in Figure 3. It will be seen from these charts, and from the opposite directions of curvature of the trajectories about Jupiter relative to the planet's rotation, that substantial diversity was achieved by the combination. In addition to the higher Jovian equatorial latitude sampled with Pioneer 11, magnetic latitudes of survey inside the radiation belt were greatly expanded. Similarly, whereas Pioneer 10 was in a nearly constant meridian plane relative to Jupiter for several hours during closest approach, Pioneer 11 traversed a full circle of planet longitudes during 4 hours at encounter. The lowest altitude reached by Pioneer 11 was 42,000 km, about one-third that of Pioneer 10's venture.

While the Pioneer 11 trajectory, in retrospect, was an obviously good choice after Pioneer 10's encounter, its selection was deliberated for several months. Maximum radiation intensity was predicted to be encountered at penetration of the magnetic equatorial plane, within 5 to 10 minutes after emergence from occultation. Risk to the spacecraft for deep penetration was acceptable, but the spacecraft could conceivably have been lost during occultation before its most significant measurements had been transmitted from its memory to Earth. The fluence of high-energy protons was predicted to be nearly equal to that encountered by Pioneer 10, although the high-energy electron fluence would be less. Results now demonstrate that predictions for intensities of high-energy electrons were fairly accurate, but predictions for intensities of high-energy protons were on the order of ten times lower than the intensities actually measured close to the planet.

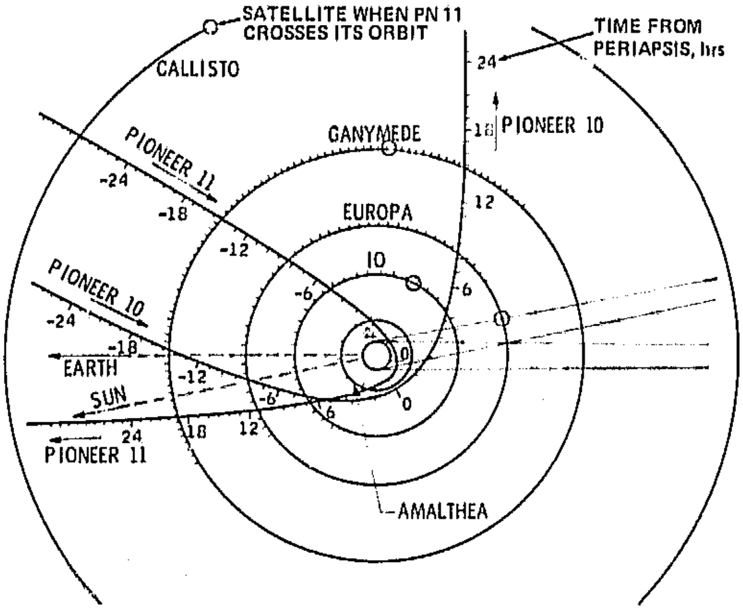


Figure 1. The Pioneer 10 and 11 trajectories referenced to Jupiter and projected into a plane parallel to the ecliptic plane.

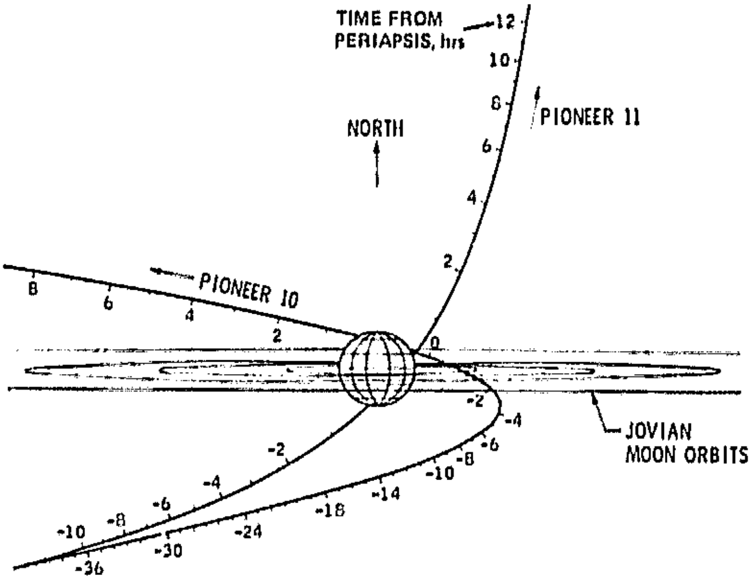


Figure 2. The Pioneer 10 and 11 trajectories referenced to Jupiter as seen from Earth.

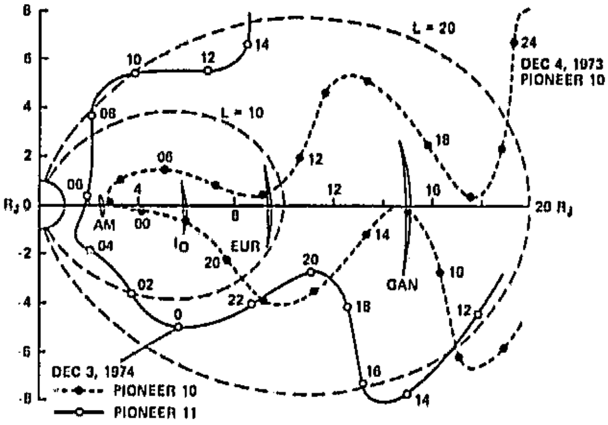


Figure 3. Projection of the trajectories of Pioneer 10 and Pioneer 11 on a magnetic meridian plane of Jupiter. The region sampled by Pioneer 10 was within ~20° of the magnetic equator, whereas Pioneer 11 trajectory was usually above 40° latitude in the inner portion of the magnetosphere.

SPACECRAFT AND INSTRUMENTS

Pioneer 11 and its scientific instruments are identical with Pioneer 10, as described by Hall[1], except for one additional instrument and certain modifications to two others.

Spacecraft

A sketch of the spacecraft is shown in Figure 4. It was designed, built, and tested by the Systems Division of TRW, Inc., Redondo Beach, California.

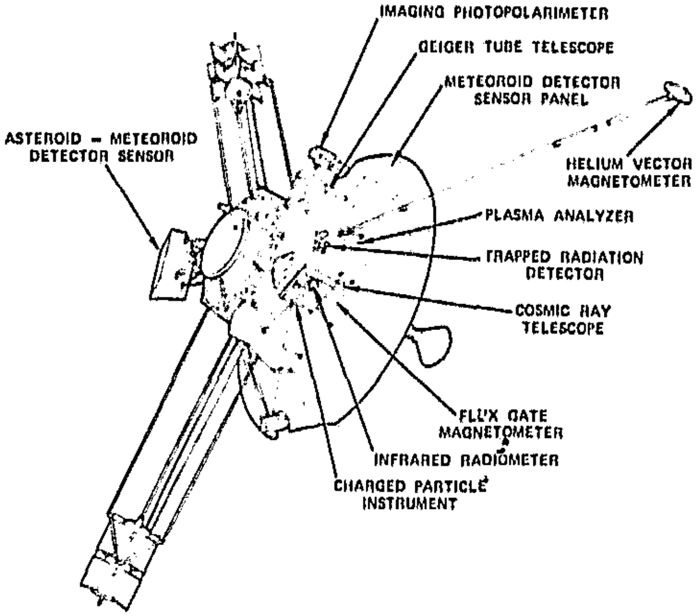


Figure 4. The Pioneer 11 spacecraft configuration showing the equipment compartment and scientific instruments mounted on the backside of the parabolic dish antenna. The entire spacecraft is spin stabilized at 4.8 revolutions per minute with its antenna pointing toward Earth.

Dominant structural features are a 2.8-meter-diameter parabolic reflective antenna with a tripod-mounted feed, a prismatic compartment for equipment and instruments centered on the backside of the antenna, two pairs of radioisotope thermoelectric generators (RTGs) on two booms extending beyond the edge of the antenna from the equipment compartment, and a 6-meter boom for the magnetometer extending, symmetrically opposite the RTG booms, from a third side of the compartment.

Total weight at launch was 258 kg. The entire spacecraft rotates approximately 5 revolutions per minute, keeping the radio beam and the instrumentation scanning patterns stabilized in space. The only significant mechanically movable component is a small telescope on the imaging photopolarimetry instrument.

Critical subsystems are furnished in duplicate to minimize risk of gross mission failure. In addition to excess power capacity, redundant components include radio transmitters, radio receivers, command decoders, data handling units, propulsion and maneuver control circuitry, propulsion thrusters, clocks, and rotational reference sensors (two sun sensors and a star sensor). In Pioneer 11, the only secondary unit to be activated to date because of unsatisfactory service has been a radio transmitter.

Reorientation of the spin axis and maneuvering propulsion are provided by catalytic dissociation of hydrazine in small thrusters, rated at 5 newtons each. Three pairs of thrusters used in various combinations affect acceleration in either direction along the spin axis, providing torquing impulses to reorient the spin axis or torque to increase or decrease the spin rate. An onboard storage programmer or direct commands from Earth can be used to activate thrusters. All thrusters are connected with a single 27-kg supply of liquid hydrazine capable of providing 200 meters/second maneuver capability after separation from the launch vehicle. About 45% of the original propellant remains aboard Pioneer 11 as it moves toward Saturn.

Electrical power is provided continuously by the four radioisotope thermoelectric generators, which produced 160 watts at launch. The original 50% excess over requirements is dissipated in electrical shunts until decay or partial failure of capacity eliminates that surplus. A rechargeable battery is carried to handle short-term peak loads.

Thermal control is achieved by use of multilayer insulation which has proper surface radiative properties, and by thermally activated louvers which expose high emissivity surfaces to space when spacecraft temperature is high.

Radio communications and data handling capabilities, and their management, for controlling Pioneer 11 and acquiring its data from the vicinity of Jupiter, are described in the following section.

DATA COMMUNICATIONS

Capability at Jupiter's Distance

NASA's Deep Space Network, with stations in Spain, Australia, and the Southwestern United States, maintains command, telemetry, and navigational telecommunications with Pioneers 10 and 11 (in addition to support schedules with other space and radio-astronomy projects). Their 64-meter-diameter steerable antennas deliver about -153 dBm to the receivers from Pioneer's 2.8-meter antenna and 8-watt transmitter at Jupiter's distance.

A data rate of 1024 bits per second can be received at very low bit-error rates, and the 2048-bit-per-second maximum spacecraft capability could have been received with reasonably low error rate had it been advantageous.

The telemetry data are convolutionally encoded with two bits per information bit convolved through a moving 32-bit sequence. Parity check and error correction in ground-based computers with this encoding system results in demonstrably effective gain near the theoretical maximum 3-dB signal-to-noise ratio.

The radio signal from Earth, for command and continuous coherent reference at the spacecraft's transponder, is provided with ample margin by only a small fraction of the ground station's 400 kW maximum capability. In fact, the spacecraft can be reliably commanded through its "medium gain" antenna when oriented up to 20° away from Earth alignment, if necessary.

Spacecraft Data Handling

Data from scientific instruments and engineering systems are digitally encoded and arranged into 10 formats which can be selected in certain combinations by command from Earth. Selections are structured such that a minimum flow of engineering data are continuously transmitted by means of subcommutation within science data formats. Conversely, selections of engineering or special science formats contain within them approximately a 3% mix of subcommutated scientific data from a variety of particle and field sensors. Table 1 outlines the emphases of the formats and describes how they can be combined into the radio transmission.

TABLE 1. PIONEER 10 AND 11 TELEMETRY DATA FORMATS

Designation[a]	Type	Purpose/Emphasis
A	Science	General purpose interplanetary science
B	Science	Similar to A, modified for inside radiation belt
C1	Engineering	Spacecraft functional status, electrical power, roll reference timing
C2 [b]	Engineering	Thermoelectric generators, radio communications
C3	Engineering	Stored commands, spin axis orientation, propulsion
C4	Engineering	Roll rate, star reference, maneuver control
D1	Science	Imaging photopolarimeter data (buffered)
D2 [c]	Science	Infrared radiometer and imaging (buffered)
D3	Science	Plasma analyzer in fully analytic mode
E1 & E2[d]	Science	Status of most instruments, data from five

[a] Each format designates content of a frame consisting of 192 sequential binary bits.

[b] Formats C1 through C4 can be selected as a continuously sequential set. Together, they contain all spacecraft engineering data in 165 parameters. Most of the content is subcommutated in Formats A and B.

[c] Formats D1, D2, or D3 can be selected only in alternating frame combinations with formats A or B; e.g., A/D1, A/D2, or B/D1, etc.

[d] Formats E1 and E2 are alternated with each other, and are only subcommutated within formats A, B, and C1 through C4.

Rates at which data are transmitted from Pioneers 10 and 11 are selectable from 16 to 2048 bits per second (2^n, where $n = 4$ through 11). The rate selection is independent of format selection (though certain scientific data formats would not generally be useful at slow rates), it is usually dictated by the distance to the spacecraft and size of the available ground station antenna such that the modulation can be detected in the receiver. Rates as low as 64 bits per second have been used beyond Jupiter's distance with 26-meter ground receiving antennas.

Storage of data in the spacecraft is in a 49,152 binary bit magnetic core unit. It can be filled only in the same format as is selected for radio transmission, and at that same bit rate. Memory readout can be commanded at any bit rate desired, but cannot be interleaved with other data. The last 6,144 bits (one eighth) of the memory are used by the imaging photo polarimeter to buffer imaging data taken over a limited sector (usually 30°) of each spacecraft rotation so that the image data can be transmitted to Earth at a consistent, practical rate.

Command Control

Commands are encoded for transmission in sequences of 22 binary bits: 7 bits address the spacecraft to insure against response to commands intended for other spacecraft; 11 bits constitute the actual instruction; and 4 bits verify the total message. Command coding requires 22 seconds for each individual command, but the spacecraft carries storage capability for five commands which can be loaded from the ground and later executed in more rapid successions. Each stored command has associated with it a delay interval, also programmed from Earth, which controls its sequential timing. A total of 246 discrete commands are recognized and acted upon by the spacecraft, and 256 preprogrammed values can be entered by command into the several timing and counting registers in the spacecraft. About one-third of the command designations are for direct control and services to scientific instruments.

Encounter Operations

Actual command usage varies widely according to the scheduled activity of the day. Enroute to planetary encounter, some tracking intervals are occupied with commands to reorient the spin axis, to adjust velocity vector by propulsive maneuvers, or to measure orientation relative to a star (or the Sun) and Earth. Periodically, sky surveys of zodiacal light are made. Also, spectral analyses of ions and electrons in the solar wind are conducted when time is available for dedication of a large proportion of the data stream.

Approximately 1,300 commands were transmitted to Pioneer 11 on each of the two days at closest approach. In quantitative terms, most (over 90%) were to control the movable telescope, the modes (i.e., imaging or polarimetry), and the gain of the imaging photopolarimeter.

Many of the commands transmitted close to the time of encounter with Jupiter were intended not to effect any reaction within the spacecraft at all. Rather, they were sent to be sure equipment would continue operating in correct configurations in spite of severe radiation, and without awaiting the 80-minute radio propagation time for two-way communications with Earth. A list of commands was prepared to keep the spacecraft with the proper data format, data bit rate, transmitter on,etc., and to maintain some scientific experiments powered and in their intended operating modes. The telescope of the spin-scan imaging photopolarimeter, for example, was periodically reset to an index position and redirected from there to its scheduled aspect angle. This list of commands, expanded from our earlier experience with Pioneer 10, was transmitted every 30 to 40 minutes during Pioneer 11's two encounter days.

Other command messages to the spacecraft were to change data formats for science emphases as encounter geometry changed, to calibrate certain instruments, to configure for very low rate of data recording during the 40-minute occultation, to adjust roll angle aperture location of the infrared radiometer, etc.

False commands were produced by the Jupiter environment in spite of the precautions. Most of the false commands resulted in unwanted shifts of the imaging photopolarimeter telescope. The most serious radiation effect resulted in timing the infrared radiometer's observation in each of the spacecraft's rotations such that the northern part of Jupiter was being missed. Upon emergence from occultation and maximum radiation flux, the error in the radiometer's roll angle aperture was detected; correction required 189 incrementing commands. About half of the planned northerly infrared mapping was missed, mostly because of the 80-minute radio propogation time for telemetered status and corrective commands. No anomolies in execution of commands was observed.

The detailed control sequence was planned weeks in advance, timed to the second, and entered into computer-controlled files for verification and release during encounter. Visual verification of segments of the listed sequence was made during the operation by the same engineers who assembled the plan, and adjustments to meet exigencies were incorporated under their direction.

The predicted time of closest approach, upon which the operating plan was based, was estimated to be within ±2 minutes when the plan was completed. No adjustments were necessary in the final week, and the prediction missed by less than 30 seconds. The most critically timed sequence was that for reacquiring telemetry data upon emergence from occultation so that data in the small memory could be time annotated before it was filled to capacity. The uplink radio frequency, with dynamic corrections for Doppler shift, was swept through the predicted receiver passband three times within 14 minutes of emergence from occultation. Receiver lock on Earth was achieved immediately, and commands were accepted within 5 minutes after occultation.

Scientific Investigations

Twelve instruments are carried by Pioneer 11, one more than Pioneer 10. The instruments are listed together with the principal investigators and their sponsoring institutions in Table 2. The additional unit is a fluxgate magnetometer with dynamic range extending to 10 gauss.

TABLE 2. INSTRUMENTATION ON PIONEER 11

Instrument	Institution	Principal investigator
Helium vector magnetometer	Jet Propulsion Laboratory (JPL)	E. J. Smith
Fluxgate magnetometer	Goddard Space Flight Center (GSFC)	M. Acuna
Plasma analyzer	Ames Research Center (ARC)	J. H. Wolfe
Charged-particle detector	University of Chicago	J. A. Simpson
Geiger-tube telescope	University of Iowa	J. A. Van Allen
Cosmic-ray telescope	Goddard Space Flight Center (GSFC)	F. B. McDonald
Trapped-radiation detector	University of California, San Diego (UCSD)	R. W. Fillius
Ultraviolet photometer	University of Southern California (USC)	D. L. Judge
Imaging photopolarimeter	University of Arizona	T. Gehrels
Infrared radiometer	California Institute of Technology	G. Münch
Asteroid/meteoroid detector	General Electric Company (G. E.)	R. K. Soberman
Meteoroid detector	Langley Research Center (LRC)	W. H. Kinard

Radio Science

As with Pioneer 10, two scientific studies of the radio link were made at encounter. Celestial mechanics data are being derived under the direction of

Dr. John Anderson of the Jet Propulsion Laboratory (JPL), and occultation effects from Jupiter's atmosphere are being analyzed by a team led by Dr. Arvydas Kliore, also of JPL.

Fields and Particles

Two magnetometers were provided to measure the orthogonal vectors of the magnetic field. The helium vector magnetometer measures components over the range from 0.016 gamma to 140,000 gamma; the fluxgate magnetometer is sensitive from 1,000 to 1,000,000 gamma. The latter extended range was provided on Pioneer 11 to assure adequate response nearest Jupiter.

The plasma analyzer senses low energy protons to 18,000 eV and electrons to 500 eV at fluxes from 100 to 3×10^9 particles/cm^2/sec. Directionality of the plasma flux can be analyzed when the requisite data rate through the spacecraft is assigned by command from Earth.

The charged-particle detector, Geiger-tube telescope, cosmic-ray telescope, and trapped-radiation detector provide a diversity of sensor types, dynamic ranges, and directional resolutions to sample the spectra of high energy particles encountered near Jupiter. Additionally, the cosmic-ray telescope was designed to monitor interplanetary particles. Electrons from 0.06 to 35 MeV are observed, as are protons from 1 to about 800 MeV, by this array of instruments.

Remote Sensing

The ultraviolet photometer is a two-channel instrument designed to observe resonance of helium and atomic hydrogen. Viewing of Jupiter by the immovable ultraviolet scanner was precluded, however, by choice of the trajectory that would extend to Saturn.

The imaging photopolarimeter is designed for three basic investigations. The instrument produces color images by means of computer reconstruction of red and blue brightness measurements made in one-half milliradian pixels as the spacecraft rotates and the telescope is progressively stepped relative to the spin axis. Similar treatment is made of larger (eight milliradian) elements for polarization survey. And, in interplanetary space, dust density is measured with a wide open (2.3°) aperture scanning the sky away from the Sun.

The two-channel infrared radiometer measures planetary emissions at 14 to 25 and 29 to 56 micrometer wavelengths.

Meteoroid Detection

The asteroid/meteoroid detector consists of four parallel unfocussed optical telescopes from which size and trajectory of small particles coming within their overlapping view fields is inferred. Relative times of entry and exit of moving particles are measured, along with brightness.

The meteoroid detector consists of 234 pressurized cells which are penetrated by impact with particles more massive than 10^{-8} grams. Similar cells on Pioneer 10 were more sensitive (to 10^{-9} grams). In this way, a spectral difference between the two flights could be observed.

SCIENTIFIC RESULTS

Following is a summary of scientific results reported since Pioneer 11's encounter with Jupiter, emphasizing the advances achieved by this second flyby. This outline is largely based upon Reference 2, in which participating scientists reported early results from their data.

Magnetic Field

The closer and highly inclined trajectory of Pioneer 11 produced a more precise and detailed definition of Jupiter's magnetic field. The dipole moment was found to be 6% greater than the Pioneer 10 estimate; 4.225 gauss $R_j{}^3$ (where R_j is the radius of Jupiter, 71,400 km).

Table 3 lists the more accurate parameters of the dipole as determined from the additional Pioneer 11 data, along with the comparative values reported from the first flyby a year earlier at nearly twice the distance from Jupiter's center. No significant difference from the new magnetic field model is shown by comparing it with Pioneer 10's observational data. While adjustments in parameters are believed attributable to improved sampling, the possibility of temporal changes during 1974 cannot be eliminated.

TABLE 3. MAGNETIC DIPOLE MODEL - COMPARISON OF VALUES FROM PIONEERS 10 AND 11

Parameter	Pioneer 10	Pioneer 11
Magnitude, gauss $R_j{}^3$	4.00	4.225
Tilt angle	10.62°	10.77°
System III longitude	222.1°	230.9°
Center offset, R_j	0.11	0.101
Offset latitude	15.9°	5.12°
Offset longitude	175.6°	185.7°

Jupiter's magnetic field is now demonstrated to be more complex than a simple tilted dipole. Quadrupole and octopole components in proportions of 20% and 15%, respectively, of the primary dipole were determined. For comparison, proportions of the corresponding Earth's multipole components are about two-thirds of those in Jupiter's field components.

In the "middle magnetosphere," between about 20 and 50 R_j, the ring current theorized from Pioneer 10's encounter appeared to be reconfirmed by the magnetometer on Pioneer 11. The current sheet was penetrated at about 40 R_j inbound, at which point the local magnetic field strength diminished to a small fraction of the ambient 10 to 20 gamma, and its radial vector component reversed. Such clear evidence of the ring current had not previously been obtained near the solar meridian of Jupiter. Westward spiraling of Jupiter's magnetic field was also confirmed in the middle magnetosphere.

Passage through the magnetopause during both approach and departure, occurred three times at distances of 57 to 97 Jupiter radii. Like Pioneer 10's observations, very large-scale buffeting of the bow shock and magnetosphere by solar wind appears to have been experienced.

The general picture, then (of a hugh magnetosphere, on the order of 1/10 astronomic unit across, which is blunted by the solar wind and which contains a ring current in its middle equatorial volume), appears sustained by the magnetometers in the second sampling.

Electron and Proton Flux

Bursts of low-energy protons from Jupiter were discovered from Pioneer 11 at least two days before entering the planet's magnetosphere. Close to Jupiter's bow shock, periodicity of the bursts of charged particles emitted from the Jovian system are shown to maintain approximate phase coherence with Jupiter's synodic rotation period through the year between Pioneers 10 and 11 encounters. Time-phase reversal of particle bursts, as they are observed from above and below the magnetic equatorial plane, is not evident in the outer magnetosphere and outside the magnetopause, however. Thus, the mechanism by which charged-particle bursts are ejected from Jupiter's vicinity cannot be simply visualized.

Charged-particle data showed abrupt rises inside the magnetopause. Low-energy protons were shown to be compressed against the bow shock while that surface was pushed ahead of Pioneer 11 for one day, during its approach through 92 to 78 R_j.

Particle intensities varied inside the magnetosphere with the 10-hour period of the planetary rotation, again demonstrating magnetic latitude dependence of trapped-particle flux. The spectral index, indicating proportions of high-energy particles, also modulated with the same period, but inversely with flux. Spiraling of the high-energy particles to greater latitudes is thereby generally shown. However, after northward crossing of the magnetic equator near the closest approach, the spectral index was in phase with flux, indicating high density of low-energy particles in the high northerly magnetic-latitude volume traversed by Pioneer 11.

While the basically dipolar magnetosphere of trapped particles modified by distension and ring current appears confirmed, a much more complicated model is needed to explain the unpredicted flux intensity at high latitude. Better understanding of this feature is believed by investigating scientists to be a key to describing particle transactions between Jupiter's magnetosphere and the solar wind. Measurements in the magnetosheath in the anti-solar direction from Jupiter were not available from Pioneer 10 and 11 trajectories, but are believed essential for defining a satisfactory model.

In the "middle radius" of the magnetosphere, from about 50 to 20 R_j, no radial dependence of average particle flux is noticeable in any of the instruments for either electrons or protons. As the spacecraft moved inward, however, strongly increasing organization of the particles relative to latitude is evident. Data taken while outbound through that same radial range indicated a higher average flux with less magnetic latitude dependence. The contrast of

Pioneer 11's high-latitude outbound data with data from the other three traverses of this middle region by Pioneer's 10 and 11 is interpreted to demonstrate very strong blunting of the magnetosphere and its trapped particles by the solar wind. Pioneer 11 departed Jupiter within 10° of the noon meridian plane.

Directional motion of protons of about 1 MeV in energy was found strongly corotational with the planet throughout the outer and middle radii of the magnetosphere. These observations, together with magnetometer data cited above, directly show the ring current inferred from Pioneer 10 data.

Strong transient anisotropic bursts of protons with energies of about 1 MeV near the orbit of Ganymede, at around 15 R_j, suggest the existence of localized accelerations within the magnetosphere. A sequence of, typically, one-minute bursts continued for several hours.

The inner magnetosphere appeared to contain a very stably trapped field of energetic particles. Crossover points in magnetic latitude and radius of the Pioneer 11 and 10 trajectories were faithfully repetitive in measured radiation levels. A peak flux at about the 3.4 R_j magnetic shell was again observed. Total electron dosage to the spacecraft was less than with Pioneer 10 because of the highly inclined relative trajectory, and because the flux profile leveled considerably inward from the 2.85 R_j closest observation by Pioneer 10. Figure 5 shows the comparison of observed high-energy particles with predictions based upon Pioneer 10's lower latitude survey in 1973.

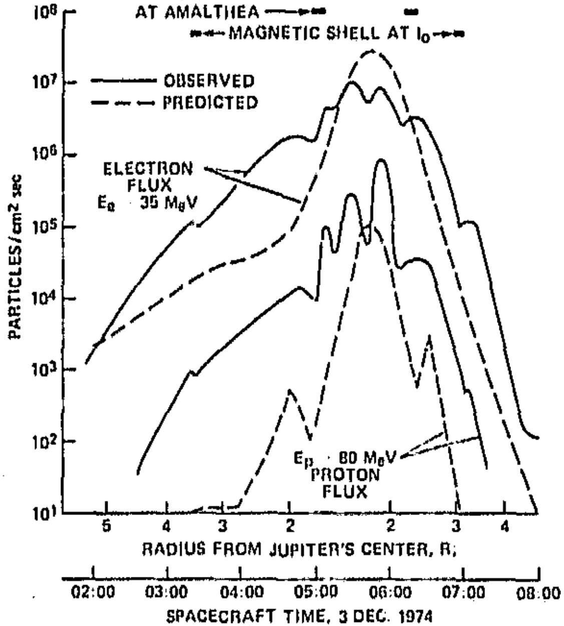


Figure 5. High-energy electron and proton fluxes observed by Pioneer 11 close to Jupiter compared with predictions modelled after data from Pioneer 10 one year earlier. The new measurements were taken closer to Jupiter's surface (to 0.6 R_j, vs 1.9 R_j), and at much higher magnetic latitudes than observed from Pioneer 10.

Limitation of flux in the innermost traversed volume appeared to be influenced by Amalthea's sweeping action, but possibly cannot be entirely ascribed to the satellite because the decrease extends somewhat outside the magnetic shells occupied by Amalthea. Variations in the innermost measurements of the charged-particle flux tend to independently confirm conclusions from magnetometer data that a more complex magnetic field than a simple titled dipole exists.

Satellite effects upon Jupiter's trapped radiation, suggested from Pioneer 10 data, are clearly established as major features by Pioneer 11's survey. Deep reductions (~99%) in electron flux for energies ≲560 keV, and in proton flux with energies ≲2.1 MeV were coincident with penetration of the magnetic shell in which Io orbits the planet. Less dramatic, but convincing, similar effects of Amalthea are observable. Europa can be associated with only a feeble hint of particle absorption in Pioneer 11 observables.

Inward diffusion of charged particles appears demonstrated by the downward shift at Io in the otherwise rising curve which relates fluxes of low-energy particles inversely with distance to Jupiter. However, because changes in flux levels are not sharply bounded at magnetic shells occupied by Io's orbit, outward diffusion from Jupiter and its satellites as sources is maintained as a possibility still to be disproven.

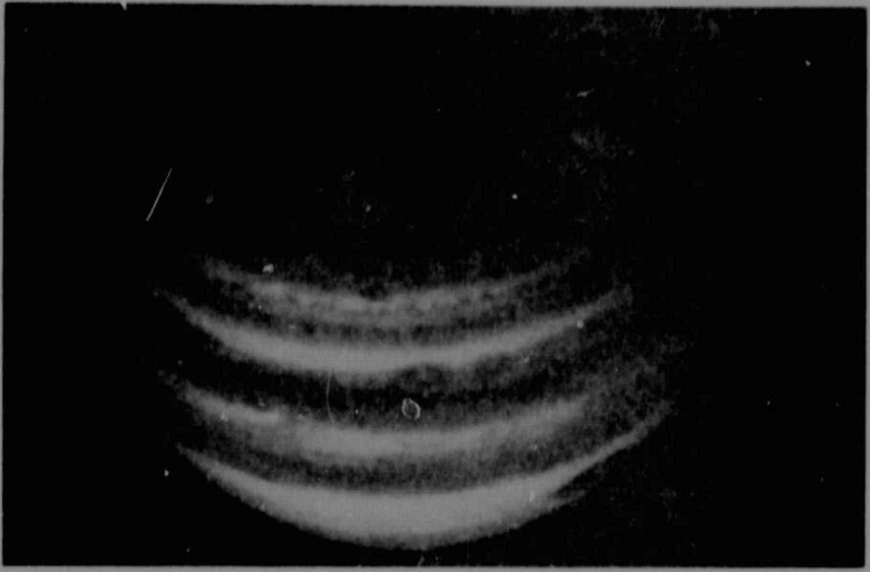
Fortuitous close passage of Pioneer 11's trajectory, chosen on other bases, near Io's magnetic flux tube (i.e., the Jovian magnetic field line which contains the instantaneous position of Io) verified the theorized high electron current along that magnetic path. Electrons with energy above 0.46 MeV (but not much above 8 MeV) increased by about a factor of 10 in the last 20 minutes approaching Io's flux tube. The other three passages through the magnetic shell containing Io's orbit (i.e., Pioneer 11 outbound and both Pioneer 10 traverses) do not show this pronounced singularity in electron flux observed near the magnetic flux tube.

Infrared Radiometry

Pioneer 11's trajectory improved coverage of Jupiter from the infrared radiometer by two spin-scan images centered at 41°S and 52°N latitudes, to complement the 11°S centered image from Pioneer 10. In spite of some loss of the northerly data because of radiation effects upon control circuitry, an improvement was made in our estimate of the planet's thermal balance. The ratio of total emitted thermal energy to absorbed solar energy of Jupiter is now estimated as 1.9 ± 0.2, not significantly different from the Earth-based estimate of 2.5 ± 0.5. Equivalent effective black body temperature is 125° ± 3°K.

Imaging and Photopolarimetry

Imaging at high latitude, especially toward the north pole, was possible from Pioneer 11 near Jupiter. North of the north temperate belt, dark belts and light zones are successively less organized until the banded structure appears to give way entirely to oval and circular features within 10 or 15° of the pole. Comparison of blue and red images reveals greater detail in red near the pole, suggesting a greater atmospheric thickness above polar clouds than above temperate and equatorial zonal clouds. Molecular scattering of blue light by deeper gas is theorized to cause the unusual superiority of images in red there compared with images in blue light. Figures 6 and 7 are images of the north polar region made from Pioneer 11. Additional views from Pioneer 10 can be found in Reference 3 and from Pioneer 11 in a forthcoming similar publication.



NASA PIONEER 11 UNIV ARIZ
RANGE: 1300000 KM PHASE: 40 LCME: 60
MID TIME OF DATA RECEIPT 3 DEC 23:26 UT
D10 BLUE DATE 12/4/74

Figure 6. View of Jupiter (in blue light) 17 hours after closest approach. The South Tropical Zone containing the Great Red Spot is the southernmost visible cloud feature. The terminator crosses Jupiter's north pole at the top center of the figure.

Efforts have been made to estimate, from photopolarimetry, the optical depth of atmosphere above the cloud tops. A model was developed for the transparent upper atmosphere for which measurements of light intensity (blue) and of polarization would match the theoretical trends as functions of solar-scattering angle variations. Surface reflectivity data were taken from Earth-based studies for lack of absolute calibration of the photopolarimeter, but model dependence upon reflectivity was shown to be small. The result is a series of estimates strongly correlating optical depth with latitude, with depths that are approximately three times greater above 60° latitude (both hemispheres) than in the equatorial areas. Investigators caution, however, that a thin high-cloud layer, or absorption in the upper atmosphere not accounted for, may make their initial model somewhat misleading. Efforts will be continued to model thin-cloud structural effects at extreme scattering angles in the hope of better understanding Jupiter's atmosphere above the visible cloud deck.

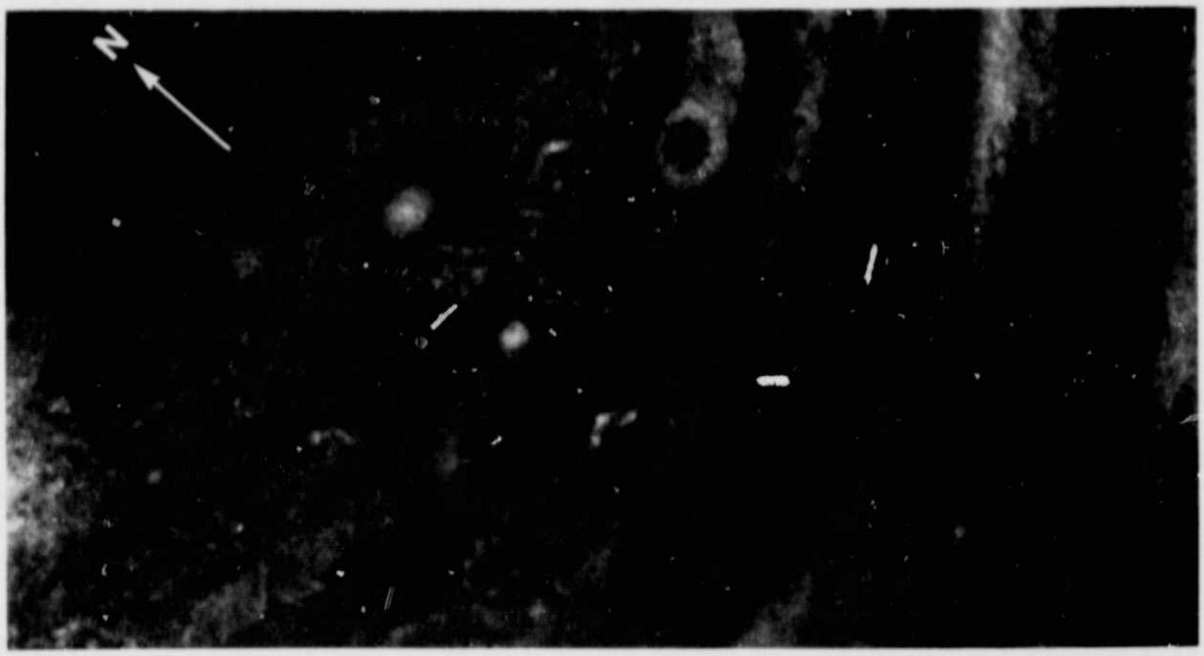


Figure 7. One of the closest images of Jupiter (in blue light) from Pioneer 11, taken about 6-1/2 hours after pericenter. Latitudes up to 72° are visible, showing the transition from banded to locally cellular cloud structures toward the pole.

Meteoroid Detection

While the primary objective of the meteoroid detector was to measure particulate distribution in interplanetary space, and especially through the asteroid belt, a surprising increase in density of particles was registered by Pioneer 10 as it flew past Jupiter. One hundred times the interplanetary dust density was inferred from particle penetrations within a few radii of the planet. Apparently, particles are either in orbit about Jupiter, or are gravitationally attracted to Jupiter from interplanetary space.

The Pioneer 11 meteoroid detector sensed fewer interplanetary particles consistent with its less sensitive design. The spectral difference in particle densities was consistent with distributions previously measured with similar designs near Earth. The gradient outward from the Sun had the same configuration as the Pioneer 10 data, except at Jupiter encounter, where about half the proportionate flux was recorded. The newer encounter experience from Pioneer 11's steeply inclined trajectory is consistent with the concept of gravitational focussing of particles toward Jupiter from interplanetary space.

S-Band Occultation

A particular objective with Pioneer 11 was to study the gross disparity between atmospheric temperature profiles obtained from Pioneer 10's occultation measurements and temperatures measured by radiometry from Pioneer 10 and from Earth. To eliminate any question of frequency drift, Pioneer 11's transponder was coherently controlled in frequency from Earth during entry penetration of the radio path, rather than its transmitter being switched to the crystal control mode as was done with Pioneer 10.

Neglect of Jupiter's oblateness was shown, early in 1975, to have induced major distortions in analyses of occultation data from Pioneer 10 and the earliest Pioneer 11 reports.[4] Subsequent derivations of temperature profile within Jupiter's atmosphere, using data from the entry and exit of Pioneer 10's radio path and the exit of Pioneer 11's radio path, are consistent with each other and with other observations.[5] However, Pioneer 11's exit data appears substantially degraded by either, or both, the effects of intense radiation or of incomplete warmup by the free-running oscillator since loss of Pioneer 11's Earth-based frequency reference at its entry behind Jupiter. Pioneer 11's radio-ray entry data has not yet been analyzed because of the complexity of two-way transmission separated by nearly one second of round-trip light time between the atmosphere and the transponder.

A distinct temperature inversion, rising from about 100°K at 100 millibars to above 140°K at 10 millibars altitude, is consistently shown in the data. Radiative-convective models and a model based upon Pioneer 10's infrared radiometer data are shown to be consistent with these observations of Jupiter's atmospheric temperature profile.

Gravity Field

Celestial mechanics analysis of Doppler data from the closer approach of Pioneer 11 to Jupiter yielded substantial improvements in estimates of zonal gravity harmonics. Hydrostatic equilibrium is consistent with the new small limits placed upon J_3 and J_6, and the density profile of the outer envelope composition models will be more tightly constrained by new precision in knowledge of J_4.

Engineering Effects

While substantially higher fluxes of protons and electrons were experienced by Pioneer 11 than 10, especially in the upper energy ranges, the integrated dosage was less. Passing within 1.6 radii from Jupiter's center, Pioneer 11's time inside 4.0 radii was 4.7 hours, only 0.4 hours longer than the slower Pioneer 10 flyby. Because of the comparative steepness of the trajectory relative to the magnetic equatorial plane, as indicated in Figure 3, however, only about one hour of that time was spent within the range of low latitudes occupied by Pioneer 10 at close distance. Whereas flux levels at high latitude were greater than predicted on the basis of Pioneer 10's data, the gradient with latitude was still sufficient to protect against damaging radiation dosage. No sensible damage was sustained by the Pioneer 11 spacecraft, itself, as a result of the Jupiter encounter. Electronic circuits in two of the scientific instruments it carries were degraded, however.

Beginning about 10 hours before periapsis, the generation of a number of spurious commands changed subsystem and instrument operations. Static discharge and high-energy radiation are believed to have caused these mode changes. Only minimal losses were sustained at the encounter from these mode changes, other than by the infrared radiometer, as indicated above.

Beginning several weeks after the encounter, spurious commands were again generated, aperiodically, for the next two months. One instrument, the asteroid/meteor detector, is tentatively identified by trial and error as the source of false sporadic commands, and has been turned off. A possible consequence of our experimentation to isolate the source of command interference is loss of the plasma analyzer, which refuses (to date) to return to operation since its power was temporarily interrupted.

EXPECTATIONS AT SATURN

Pioneer 11 will encounter Saturn in September 1979.

Scientific Objectives

Objectives at Saturn for Pioneer 11 will be similar to those already accomplished at Jupiter. Particular emphasis is placed upon those measurements which might be uniquely achieved with this spacecraft, considering the planned flights past Saturn of the two Mariner Jupiter-Saturn spacecraft only 1-1/2 to 2 years later.

A theoretical capability of swinging by Saturn to continue to Uranus, in December 1985, has been identified, but will almost surely not be chosen. Unique capabilities at Saturn would be forfeited for the extremely low likelihood of an important gain at Uranus.

Unique capabilities at Saturn are: (i) advance exploration, which might offer some information useful in final targeting of the Mariners; (ii) spin stabilization, which facilitates a most precise gravitational observation with the extraneous effects of outgassing restricted to the direction of the spin axis; and (iii) comparative freedom from subsequent mission objectives which would limit acceptability of risk in Saturn's rings.

As a precurser for Mariner, suggested direct contributions to that mission are verification that Saturn's ring plane can be penetrated near 4 Saturn radii (visible rings are bounded at 2.3 R_S, but particulate material is believed to exist well outside of that limit) and measurement of the Titan's mass and improvement in its ephermeris. The first of these two purposes is incompatible with the more likely target selections described below.

Pioneer 11's celestial mechanics potential might best be realized by penetrating between the innermost visible ring and Saturn to produce complementary data with that from Mariner's "outside" flyby. The combination of data from two such missions would produce an estimate for the mass of Saturn's rings that would be distinct from the gravitational harmonic of the planet itself. Closeness of approach will be important for measurement of gravitational harmonics and improving knowledge of the internal composition of Saturn. Much of the advantage to gravitational measurements of closeness might be achieved even if Pioneer 11 were destroyed in the "D" ring, i.e., the recently discovered ring structure inside the A, B, and C rings.

Whatever is learned about the environment of Saturn (using Pioneer 11), in terms of magnetic field and charged particles, will be defined best by deep penetration into that environment. Inferences about relative ring composition may be possible also from interactions with the magnetosphere, if a magnetosphere exists. Because Pioneer 11 will have completed its primary mission objectives at Saturn, and will be seriously limited in subsequent electrical life, it presents an opportunity to venture close at very minimal cost.

Titan is known to have an atmosphere, and is a prime candidate in the search for extraterrestial life. Pioneer 11, if it survives penetration of Saturn's ring plane near the planet and rings, could measure the mass of Titan, obtain a modest image of very gross features, measure temperature, and perhaps improve the satellite's ephemeris.

"Target" Selection

The final selection of trajectory for Pioneer 11 to fly past Saturn has not been made, and may not be until 1977. Immediate improvement in the Saturn-bound trajectory is planned beginning December 1975, in order to reduce miss distance from 2,000,000 km to about 50,000 km, and to establish a productive interim trajectory.

Several scientific interests, and the approach velocity vector, constrain the likely choice. Remaining uncertainty in our final selection depends almost entirely upon unknown characteristics of Saturn's rings. Every affected scientific interest, except for the imaging and ultraviolet scanners, would benefit from closest possible flyby. The ultraviolet scanner is mounted with its aperture oriented 20° from the spin axis pointed away from Earth, such that satisfactory scan of Saturn can be accomplished only by approaching the right and south quadrant. Occultation of the radio link by the planetary sphere without confusion from visible rings is possible only in limited sectors of the targeting map. Desire to view penetration of Saturn's ring plane from Earth's radio receiving stations also limits selection of trajectories.

Fortunately, the same targeting volume that is most scientifically productive near Saturn itself would result in escape toward Titan, providing only that arrival at Saturn be late September 1, or early September 2, 1979. Time of arrival at Saturn, as with any distant planet, will be controlled to allow duplicate recording of telemetered data by two Deep Space Network tracking stations. The earliest practical date of arrival is preferred to keep the Earth-Sun direction as far as possible away from the September 10 superior conjunction with Saturn so as to reduce solar radio noise. Choice of September 1 satisfactorily isolates the radio path from the Sun, and can be reached with a practical midcourse maneuver.

Two target locations are tentatively selected, one for the interim, and one as a future option. Flyby trajectories for both are shown as viewed from Earth in Figure 8. In addition to meeting most of the scientific interests noted above, they are so related as to make the final maneuvers simple after the selection is made.

The "outside" target results in penetration of Saturn's ring plane just outside the visible A ring, flight somewhat parallel to the ring plane with

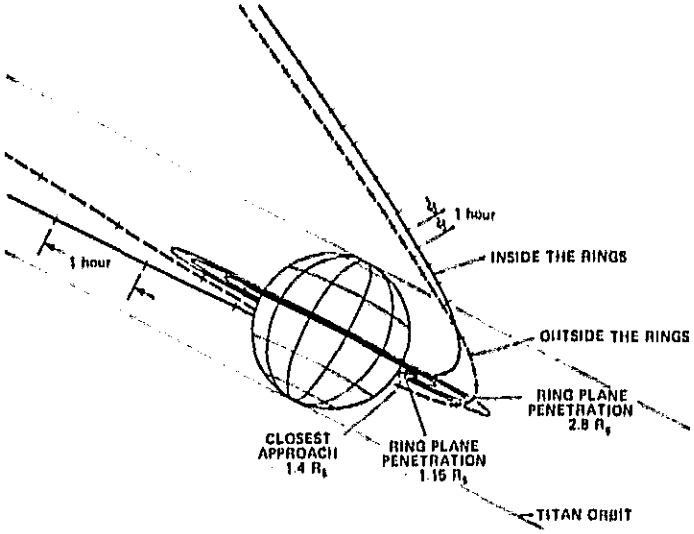


Figure 8. Two proposed trajectories referenced to Saturn and its rings as viewed from Earth. One of these flybys might be selected in 1977 as the target for subsequent midcourse maneuvers.

closest approach at 1.4 Saturn radii, and escape past Titan. Arrival at Saturn would be timed during good tracking from both Madrid and Goldstone Deep Space Network stations, about 19:00 Universal Time on September 1, 1979.

The "inside" target results in penetration of Saturn's ring plane well inside the visible rings, but directly through the "D" ring discovered photographically by Guerin.[6] Penetration of this D ring might be attempted because: (i) there is the potential for obtaining unique data on Saturn's mass properties, magnetic field, and charged-particle environment; (ii) there is at least a small possibility that spatial density of particulate material would be low enough to allow safe passage; and (iii) scientific gain from such a close approach, even with destruction there, might be sufficient to accept high risk. From these considerations, one can realize the advantages of postponing a final choice.

A maneuver to move Pioneer 11's trajectory from the "outside" to "inside" target would be made in 1978. At that time, the line in space from the spacecraft to Earth will be exactly the velocity vector direction required to make the transition. Pioneer 11 is most reliably and accurately maneuvered along its spin axis by firing selected thrusters and directly observing the Doppler change in the coherent radio link. This strategy provides the opportunity, also, to compensate for navigational error in adjusting to the critical inside passage. Time of spacecraft arrival at Saturn would be made earlier by 4 hours. This time differential, of course, will be arranged to allow dual tracking for either target selection.

Projected Capability

All of the nine scientific experiments on Pioneer 11 designed for planetary encounter observation are fully operational. Radio communications are projected to be sufficient for celestial mechanics studies of the Saturn system and for occultation study of its atmosphere. In addition, at least two-thirds of the 234 micrometeoroid detection cells will probably remain unpunctured before encountering Saturn's influence. However, the optical asteroid/meteoroid detector may have to remain turned off to eliminate electrical interference within the spacecraft, and the interplanetary plasma analyzer is unresponsive.

Electrical power availability through 1979 in sufficient quantity to operate all instrumentation was in doubt during 1973 after launch of Pioneer 11. Radioisotope thermoelectric generators have not been proven for seven years duration, and degradation observed with the new design on Pioneers 10 and 11 was not completely reassuring for this extended mission. Today, however, both spacecraft indicate a regular exponential degradation that projects full capability at Saturn, provided that all four of the units continue to degrade at their demonstrated rates.

No degradations or life limitations other than electrical power are of concern. Propellant for midcourse maneuver and maintaining Earth pointing of the antenna is sufficient for requirements with about 50% projected reserves. The midcourse maneuver, planned in December 1975, will involve the unprecedented risk of a preprogrammed reorientation of the spacecraft's radio antenna pattern far from Earth's direction, and return after two hours or more. Past performances close to Earth and the availability of backup recovery modes of control reasonably assure a safe maneuver operation.

Data rates from Saturn's distance will be limited to 256 or 512 bits per second, compared with 1024 received from Jupiter. The higher rate will be useable if solar noise is not extreme and/or if a significant error rate is acceptable to scientists. In either case, the effect of such lower rate on scientific data return is minimal except for imaging. The pictures of Saturn would be constrained to sectors one-half or one-quarter the scan arcs produced at Jupiter. Other instruments would also transmit less data to Earth; typically the effect will be to diminish the statistical resolution of directional spectra from certain charged-particle monitoring instruments.

Beyond Saturn

After its encounter with Saturn, Pioneer 11 will be moving approximately in the ecliptic plane, oppositely directed from Pioneer 10, on either of the most likely final targetings described above. Its flight direction will be close to the solar system's velocity direction through our galaxy, raising a slight possibility that the solar bow shock will be punctured and the interstellar medium visited. Such fortune would be considerably dimmed, however, if Pioneer 11's recently muted plasma analyzer cannot be reactivated. If trajectory past Saturn is as predicted above, Pioneer 11 will reach its approximate limit of data communications at 20 AU in 1986.

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