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EXPLORING BEYOND THE PLANETS: THE PIONEER 10 AND 11 MISSIONS

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The Pioneer 10 spacecraft is now further from the Sun than all of the nine planets and is the most distant man-made object in our Solar System. Pioneers 10 and 11 were launched from Earth in March 1972 and April 1973, respectively, and were the first exploratory flights through the Asteroid Belt and the first to encounter the giant planets Jupiter and Saturn. Presently, Pioneer 10 is 32 AU from the Sun and travelling toward the outer boundary of our heliosphere in a direction opposite to that of the Sun's motion through the Galaxy. Pioneer 11 is 15 AU from the Sun and travelling (in a direction opposite to that of Pioneer 10) in the "upstream" direction of the heliosphere in our galactic arm. These two Pioneer spacecraft have provided the first large-scale examination of the Sun as a star with its surrounding gas and dust. Since launch, the Pioneers have measured large-scale properties of the heliosphere during one 11-year solar sunspot cycle, and have detected the magnetic field polarity reversal that occurs every 22 years. The charged particle experiments have measured the properties of the expanding solar atmosphere, the transport of cosmic rays into our heliosphere, and the high energy trapped radiation around the planets Jupiter and Saturn. The present and future objectives for Pioneer 10 and 11 are to measure and understand the large-scale properties of our heliosphere and to search for its boundary with interstellar space.

1. INTRODUCTION

The space age began in 1957 when the first artificial satellite, Sputnik I, orbited Earth – 31 years after the flight of Robert H. Goddard's first liquid propellant rocket. Within another 22 years, spacecraft sponsored by the National Aeronautics and Space Administration had explored all the planets of our Solar System known to mankind before the invention of the telescope.

On 1 September 1979, Pioneer 11 brought these 22 years of space exploration to a climax by reaching Saturn after journeying through space for six and a half years over a distance of 3200 million km. Less than four years later, on 13 June 1983, Pioneer 10 passed beyond all the known planets in its continuing exploration of the outer reaches of the Solar System and its search for the boundary of the Sun's atmosphere and interstellar space.

The Pioneer 10 spacecraft launched in 1972 is the most distance man-made object in our Solar System. The Pioneer 10 and 11 exploratory flights were the first missions beyond Mars to be undertaken by NASA. No other nations have comparable missions. Moreover, there is no reasonable chance of getting new spacecraft to such great distances from the Sun during the present century. These two exploratory missions are probing new regions of deep space and solving many basic problems concerning the outer Solar System.

The observations obtained by the radioisotope-powered Pioneer 10 and 11 established the basic physical characteristics of the asteroid belt and, more importantly, of the giant planets Jupiter and Saturn and laid the foundations for the later detailed Voyager observations. Both spacecraft derive their electrical power from radioactive sources and are, therefore, independent of sunlight and of distances from the Sun.

After successfully completing 11 years of flight, the spacecraft have achieved an extraordinary record of reliability and accomplishments. Data obtained by the 64 m antennae of NASA's Deep Space Network is presently received at 32 bits per second from Pioneer 10 and 128 bits per second from Pioneer 11. The one-way telemetry transmission time from Pioneer 10 is presently 4.5 hours, which has significantly extended the distance over which radio telemetry data, command and control has been achieved.

Pioneers 10 and 11 are proceeding in approximately opposite directions, the latter toward the nose of the heliosphere, and the former down the hypothetical tail of the heliosphere, as shown in Fig. 1. Both Voyager spacecraft are proceeding in the same quadrant of the Solar System as Pioneer 11. These four spacecraft are providing the first *in situ* observations of the large scale structure of the Sun's remote corona which is being found to extend outward to enormous distances among and beyond the known planets.

Pioneers 10 and 11 have asymptotic escape velocities from the Solar System of 2.4 and 2.2 AU/year, respectively. There is a reasonable expectation that Pioneer 10 will penetrate the heliospheric boundary and pass into the interstellar medium before their radioisotope power outputs drop below the level of spacecraft requirements. With the present telemetry capability of the Deep Space Network, it is technically feasible to continue satisfactory reception of data until 1994.

The main goals for these two missions during the next decade are to:

(1) Search for the heliospheric boundary, termination of the solar wind and entry into the interstellar wind. The predicted lower limit for the heliocentric distance to this boundary is 50 AU, which will be reached by Pioneer 10 in 1990. The outer limit is on the order of several 100 AU. Also, study the large scale electrodynamic structure of the solar plasma and magnetic field.

(2) Measure the intensity and composition of the galactic cosmic radiation; study the radial gradient of cosmic ray intensity and its dependence on solar activity through the next minimum in 1986. Also, study the transport of solar energetic particles in the interplanetary medium and use Jupiter's point source of energetic electrons to probe the outer heliosphere.

(3) Search for a trans-Neptunian planet by observing differential gravitational forces on the two spacecraft and also search for proof of the theorised existence of gravitational radiation (also called gravity waves).

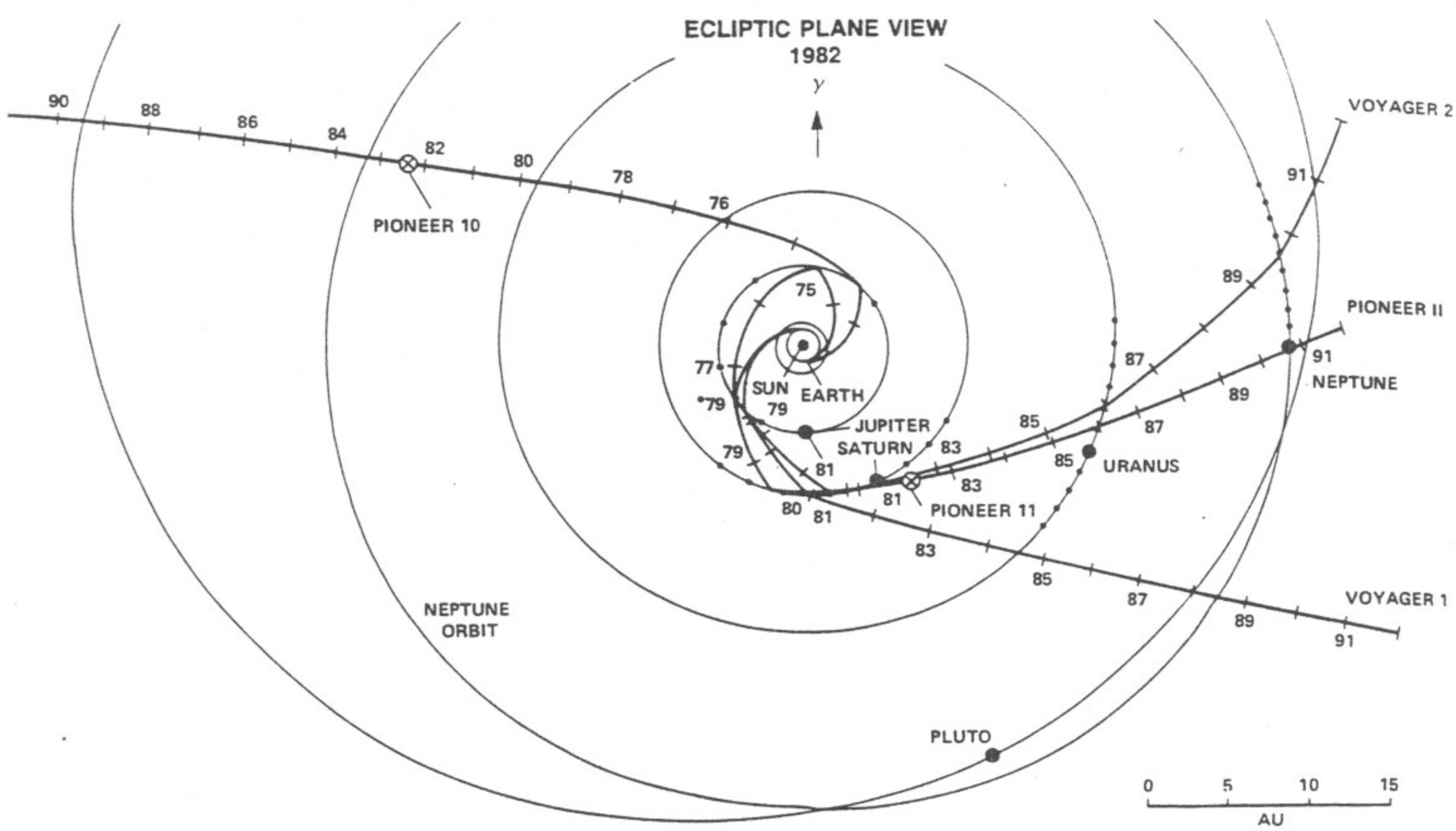


Fig. 1. Trajectories of the Pioneer 10 and 11, Voyager I and II, and orbits of the outer planets projected on the ecliptic plane.

(4) Provide baseline correlative measurements of the interplanetary medium in support of the Voyager 2 encounter with Uranus in 1986 and of the International Solar Polar Mission during its transit over the poles of the Sun.

During the past 11 years in space, these two Pioneer missions have made significant contributions to our knowledge of the interplanetary medium and have discovered many new properties of the Asteroid Belt, Jupiter, and Saturn. A partial list of these achievements follows:

(1) Determination of the large-scale structure of the interplanetary magnetic field and the flow velocity and structure of the solar wind at a very large distance from the Sun.

Pioneer 10 and 11 measurements to date have firmly established the validity of solar wind models developed during the last decade. These models, describing the spatial and temporal properties of large-scale solar wind structures, are considered to be major achievements in astrophysical plasma research. Plasma parameters observed from 1 to 20 AU determined that the average bulk speed remained constant at about 430 km s^{-1} and the proton density decreased at $6.5/R^2$ p+cm^3, where R is in AU. The temperature was found to decrease more slowly than predicted by an adiabatic expansion theory and an understanding of this phenomena remains one of the goals for this mission [1]. The magnetic field configuration conforms to the Parker spiral directions within both quiet and interaction regions, to an accuracy of 1.1° [2]. The field, at large distances from the Sun, is dominated by large-scale structures: co-rotating interaction regions, and a current sheet which divides the solar field into two hemispheres as shown in Fig. 2.

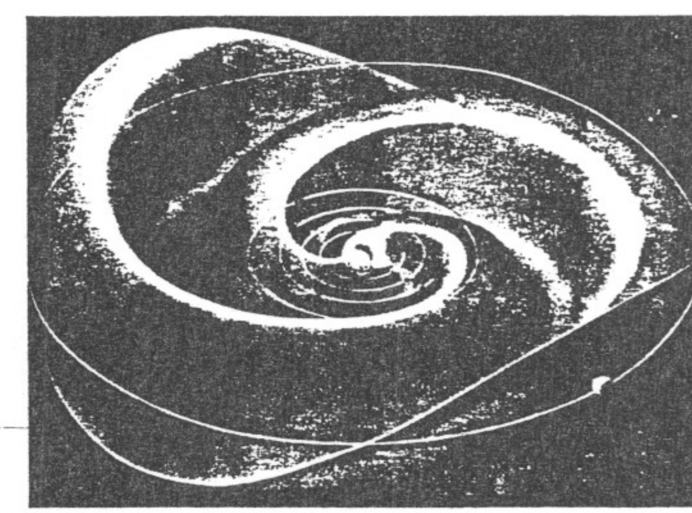


Fig. 2. A schematic of the heliospheric current sheet. Two sectors dominate the long-term magnetic field structure, and each sector adopts a Parker spiral geometry in the solar wind flowing out from the Sun.

(2) Significant advances in the measurement and understanding of the propagation of cosmic rays and solar energetic particles in our heliosphere.

One of the major accomplishments of the mis-

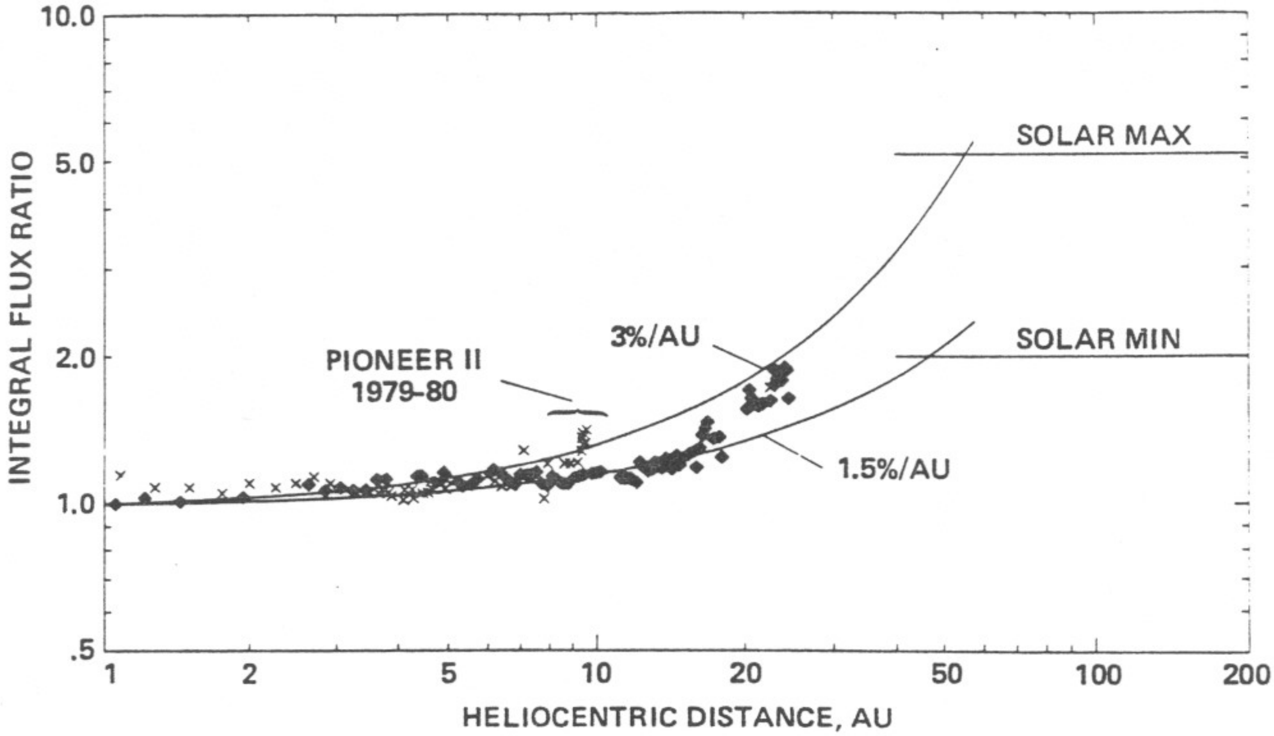


Fig. 3. Cosmic ray flux ratios for Pioneer 10 out to 24 AU to that of IMP 8 to 1 AU and Pioneer 11 out to 11 AU to IMP 8 are denoted by ◆ and X, respectively. Superimposed are radial gradient curves for 1.5 and 3% per AU. Intersection of these curves with the ratios for solar maximum and solar minimum indicate the boundary of the modulation region which is also thought to be the heliopause.

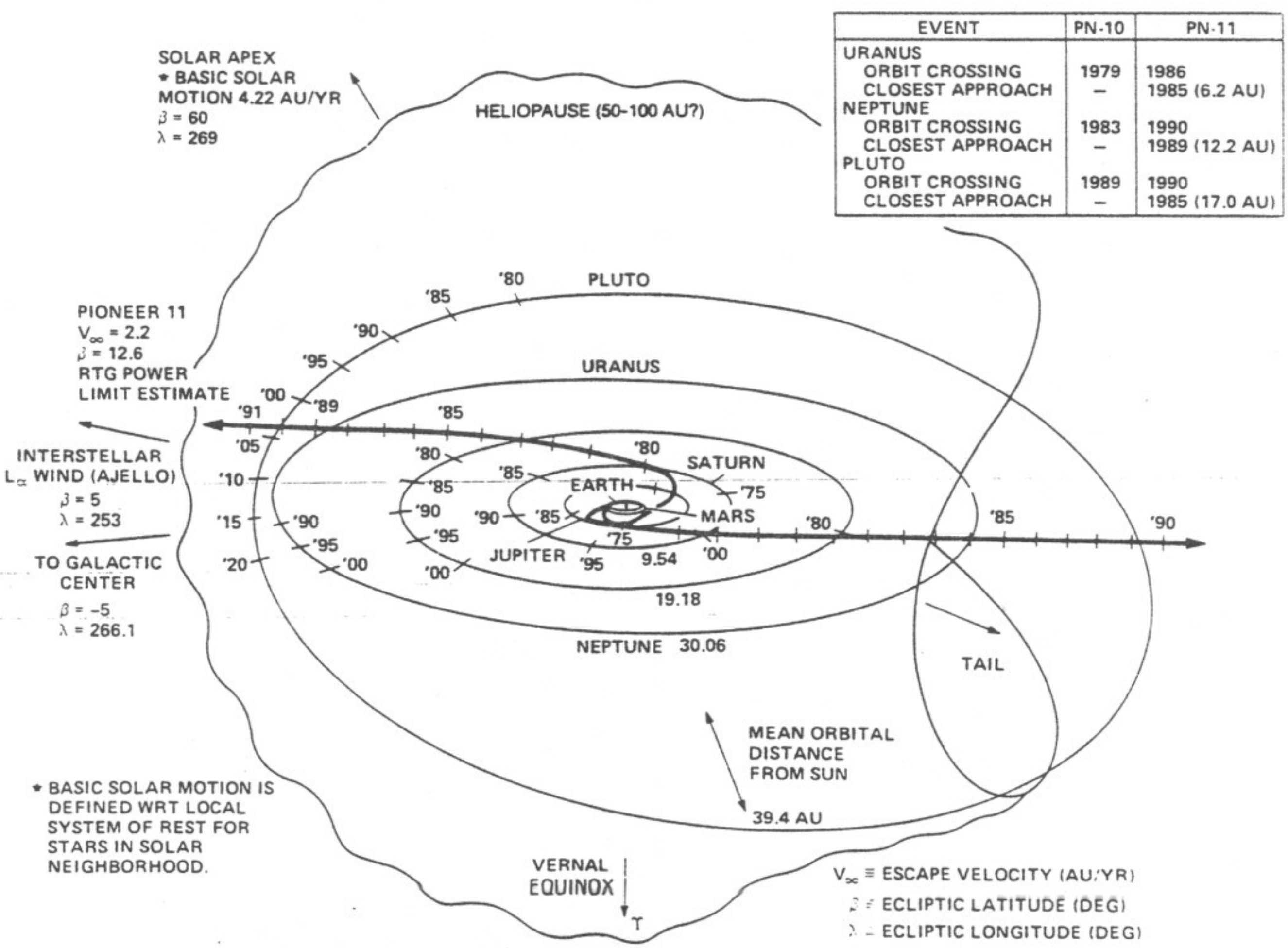


Fig. 4. Trajectories of the Pioneer 10 and 11 spacecraft as viewed 20° above the ecliptic plane.

sions was the characterisation of the energy spectra of galactic cosmic ray nuclei that are modified, or modulated, by magnetic fields being convected outwards by the solar wind. The measured radial intensity gradients are then used to estimate the depth of the modulating region, i.e., the size of the heliosphere, (Fig. 3) [3]. Recent estimates place the boundary between 50 and 70 AU [4-6]. It was found that large-scale effects such as shocks and co-rotating interactions produce major changes in the galactic cosmic ray intensities. The energetic particle detector showed that an anomalous low energy helium component is more sensitive to these modulation phenomena than is the galactic cosmic ray component. The source of this anomalous helium component is as yet unknown.

Pioneer 10 discovered a dominant source of low energy relativistic electrons to be originating from Jupiter. The Jovian electrons have been measured from Mercury's orbit out to Pioneer 10 at 32 AU and can be used as test particles to probe the entire heliosphere.

(3) Asteroid Belt.

The meteoroid and asteroid experiment onboard the spacecraft measured an actual decrease in small particles (10^{-3} mm diameter) compared to those at 1 AU. Particles with diameters between 0.01 and 0.1 mm were approximately evenly distributed from the Earth's orbit through the asteroid belt and those with diameters between 0.1 and 1.0 mm were three times more numerous inside the belt than they were near Earth. These measurements showed that the anticipated high concentration of small particles did not exist and the spacecraft emerged from the belt in February 1973 without suffering any damage.

(4) Jupiter

(a) These spacecraft were the first to measure Jupiter's magnetosphere and discover its disk-like shape. Jupiter's magnetic dipole moment is 19,000 times stronger than the Earth's, is of opposite polarity, and is tilted at about the same angle with respect to the spin axis. The field is distorted in the magnetospheric region of between 25 R_J and R_J by a strong ring current, and the bow shock was detected at 100 R_J.

(b) The measured radiation intensities of electrons trapped in the magnetic field were 10,000 times greater than Earth's Van Allen belts and peaked at 3 R_J. The protons were 1,000 times more intense and peaked in two regions, 3.4 R_J and 1.9 R_J.

(c) The infrared radiometer maps showed that Jupiter emits 1.7 times more heat than it receives from the Sun. This experiment also measured the helium to hydrogen ratio to be 0.14 ± 0.08, in close agreement to the solar ratio of 0.11.

(d) The first close-up pictures, which covered the polar regions and were three times better than Earth-based telescopic pictures, showed that the cloud tops at the poles are lower than those at the equator and that atmospheric convective cells are smallest in the polar regions.

(e) The energetic particle detectors discovered that Jupiter is the dominant source of low energy relativistic electrons in the explored heliosphere. Spacecraft travelling from the orbit of Mercury and out to 32 AU measure those electrons and have not yet found a low energy component originating outside our heliosphere. It was discovered that the Jovian electron spectrum in interplanetary space varies with the 10-hour period of Jupiter's rotation period. Jupiter's magnetospheric emission of electrons is like a 10-hour "clock."

(5) Saturn

(a) The magnetic dipole moment was determined to be 540 times stronger than the Earth's, tilted less than 1° to the spin axis, and of opposite polarity. The outer regions of the magnetosphere contained a co-rotating plasma at speeds less than that of the planet. Within a region of less than 10 R_S the plasma was found to be rigidly co-rotating with the planet. The solar wind bow shock was determined to be approximately 25 planetary radii distant from Saturn, compared with 100 R_J from Jupiter and only 15 R_E from Earth.

(b) The trapped raiation belts had comparable intensity to those of Earth, but extended over much larger regions. The maximum intensity of trapped energetic electrons and protons were found to be between 4 R_S and the outer edge of the rings. The proton flux peaked at 2.67 R_S and its source was determined to be the decay of cosmic ray albedo neutrons generated in the rings.

(c) The first clear image of an inner satellite (1979 S 1) was obtained and, in the radial range 2.9 to 2.3 R_S, five new satellite and rinf features (1979 S 2, 1979 S 3, 1979 S 4, 1979 S 5, and 1979 S 6) were observed by the apsorption that they caused in the intensity of energetic particles.

(d) The infrared radiometer measurements showed that Saturn emits 2.8 ± 0.9 times as much heat as it receives from the Sun in the infrared spectrum.

(e) The first close-up pictures of Saturn showed that the clouds are thicker than those of Jupiter and have much less contrast. The cloud belts are also narrower and more numerous.

(f) The charged particle instruments and the photo polarimeter discovered a new ring – the F ring.

Both spacecraft have an excellent array of particles and field experiments that utilise the majority of mission time in making measurements pertinent to the physical description of the heliosphere.

TABLE 1. Heliocentric Radius of Pioneer 10 and 11, AU (1 January)

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Pioneer 10	26.9	29.0	31.8	34.5	37.3	40.0	42.7	45.4	48.1	50.7	53.4
Pioneer 11	11.3	13.2	15.3	17.7	20.1	22.5	25.0	27.5	30.0	32.5	35.0

The purpose of this article is to describe the goals for this exploratory mission into the outer regions of our heliosphere and a possible transit into interstellar space.

2. THE PIONEER 10/11 MISSION, SPACECRAFT AND EXPERIMENTS

2.1 Mission Overview

Pioneer 10 is moving outward at about 2.8 AU per year in a direction generally away from the centre of our Galaxy and roughly opposite the direction of our basic solar motion with respect to nearby stars. On 1 January 1984 it was about 31.8 AU from the Sun. Its speed will ultimately slow to an asymptotic velocity of 2.4 AU per year. Pioneer 11 will leave the Solar System at about 2.2 AU per year toward the centre of our Galaxy in the general direction of the constellation Sagittarius; on 1 January 1984 it was about 15.3 AU from the Sun. Figure 4 shows the trajectories of the two spacecraft and has annotated on it the velocities ($V\infty$), ecliptic latitudes and longitudes of the escape asymptotes. Also shown are the solar apex (direction and speed of solar motion) incoming interstellar wind direction, and direction toward the galactic centre. Table 1 gives heliocentric radii of Pioneers 10 and 11 for 1 January of the years 1982-1992.

The mission objectives of Pioneers 10 and 11 included: exploring the interplanetary medium beyond the orbit of Mars; investigating the nature of the asteroid belt and assessing its hazards to outer planet missions; exploring the environment of Jupiter; finding the extent of the heliosphere and describing the interstellar medium; and, if Pioneer 10 attained its Jovian scientific objectives, exploring the Saturnian environment (Pioneer 11). Pioneer 11 was retargeted in 1974 for Saturn flyby after its Jupiter encounter on 9 December 1974. Since September 1979 the two spacecraft have proceeded in generally opposite directions toward the Solar System boundary, and continued to transmit data on interplanetary and heliocentric phenomena. The extreme range of Pioneer 10 makes possible sensitive searches for gravity waves and for a possible undiscovered planet or dark solar companion.

2.2 The Pioneer 10/11 Spacecraft

The state-of-the-health of the Pioneer 10 spacecraft and of most of its scientific instruments is excellent. Data are being acquired on a daily basis at 32 bits per second with the 64 m antennae of the Jet Propulsion Laboratory Deep Space Network.

With present Deep Space Network cpabability, it will be feasible to continue to receive error-free data at 16 bits per second until the early 1990's. In April 1990, Pioneer 10 will have reached a distance of 50 AU, or 7,479,900,000 km, from the Sun on its hyperbolic escape trajectory from the Solar System.

The projected amount of electrical power from the spacecraft's four radioisotope thermal generators (RTGs) – supplemented by radioisotope heating units – will be adequate to maintain the temperatures of the spacecraft subsystems and the instrument bay at a comfortable level and to supply the necessary electronic power for the spacecraft and most of the instruments until the early 1990's. The supply of orientation gas (for spin-axis pointing control) is more than adequate to this time period.

Figures 5, 6 and 7 show the prominent physical features of the spacecraft. It is a highly reliable spacecraft of relatively simple design in which many of the components and subsystems have already demonstrated successful performance on earlier missions. It has a thermally-controlled equipment compartment with two sections, one hexagonally shaped, and containing electronic units and the propellant tank, and the other a bay containing most of the scientific sensors and their associated electronics (the magnetometer sensor and two meteoroid detectors are external). Forward of the equipment compartment is a 2.7 m diameter parabolic reflector for the high-gain antenna. Mounted on a tripod structure forward of the reflector are the medium-gain antenna and the feed for the high-gain antenna. Three appendages are stowed within a 2.7 m cylindrical envelope at launch; they are shown in their deployed positions attained within an hour after launch. Two pairs of Radioisotope Thermoelectric Generators (RTGs) are extended approximately 1.8 m at 120 degrees spacing. The RTGs were retained in a stowed position for launch next to the equipment compartment and under the antenna reflector. The magnetometer sensor is located on the end of a long folding boom which, in the deployed condition, extends 5.2 m radially from the instrument side of the equipment compartment.

Six 4 N hydrazine thrusters are located in three clusters near the perimeter of the 2.7 m reflector. Two pairs of thrusters are aligned parallel to the spin axis for precession and velocity correction manoeuvres; two thrust tangentially for spin control. Other external features include a mast-mounted omnidirectional antenna directed aft, and a Sun sensor mounted near one of the thruster assemblies which determines the spacecraft's position in the spin cycle. Two large light shields are associated with the stellar-reference assembly, and with an optical asteroid/meteroid detector.

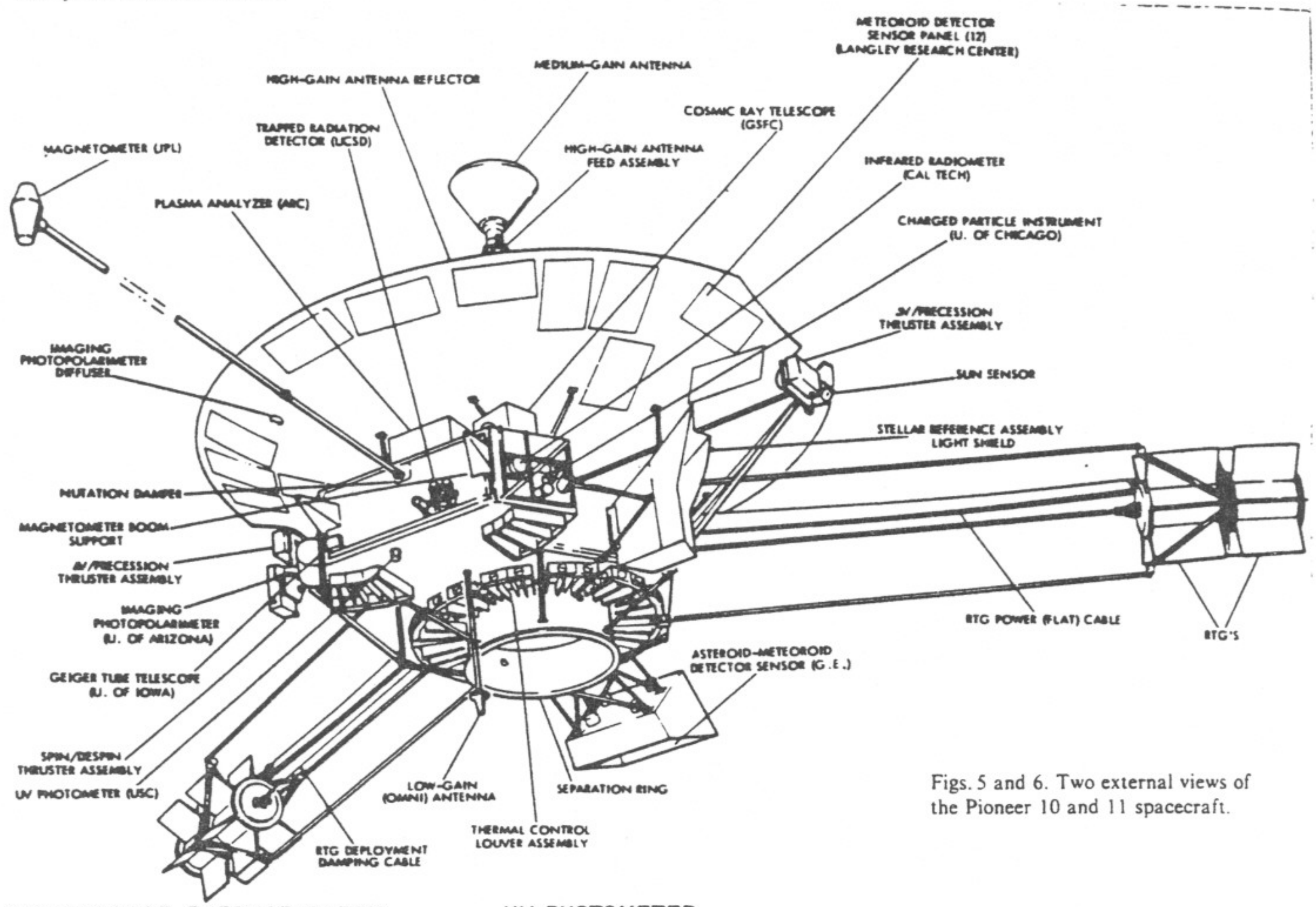
Figure 8 shows the arrangement within the spacecraft equipment compartment. The spacecraft electronic assemblies are located in the central hexagonal portion of the compartment, surrounding a 42 cm diameter hydrazine tank. Most of the scientific instruments' electronic units and internally-mounted sensors are in an instrument bay mounted on one side of the central hexagon. This equipment compartment is contained within a structure of aluminium honeycomb which provides support and meteoroid protection. It is covered with insulation which, together with louvres under the mounting platform, provide thermal control.

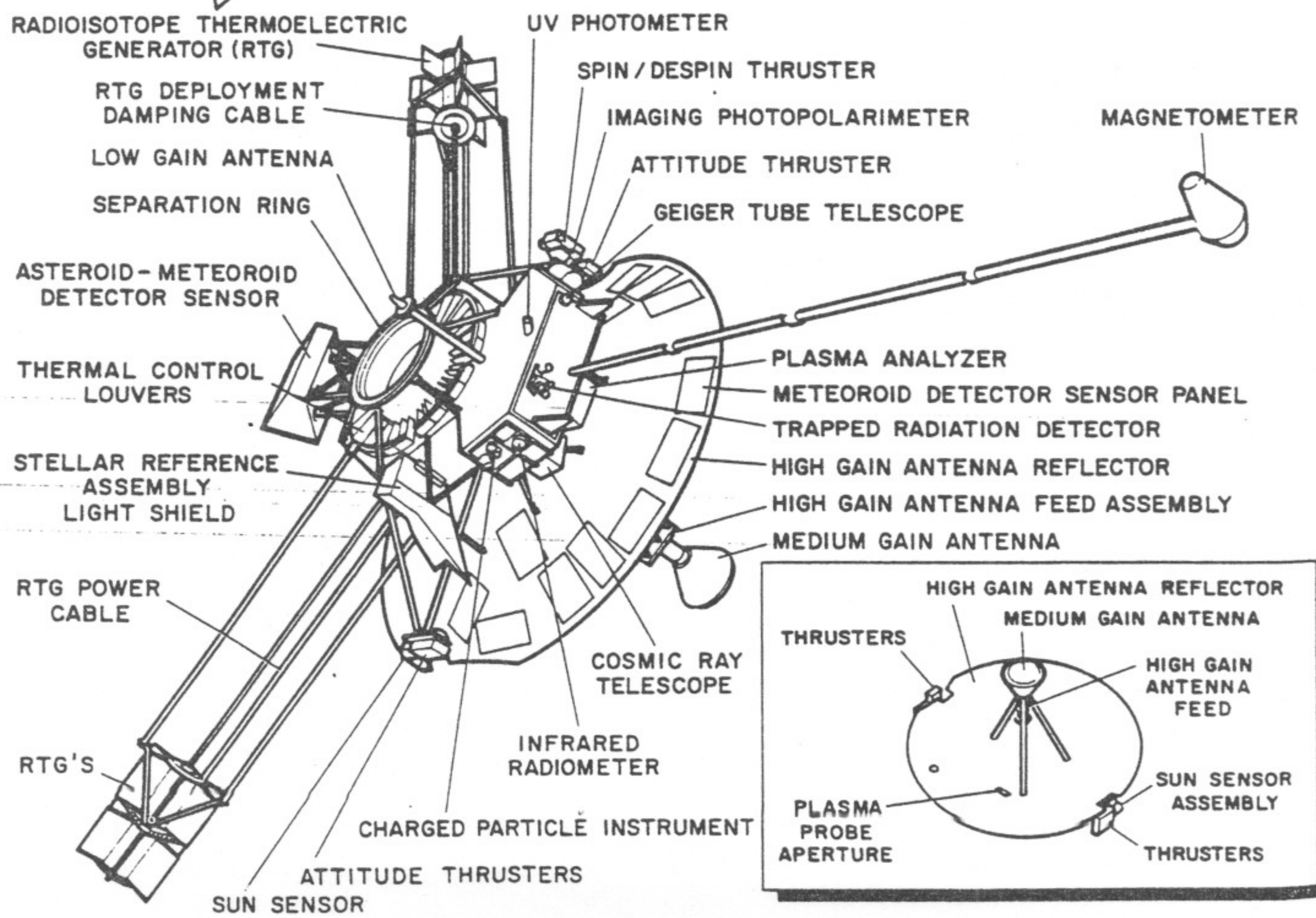
2.3 Scientific Experiments

There are ten scientific instruments on the two nearly-identical spacecraft. Brief descriptions of these investigations are given below.

2.3.1 Helium Vector Magnetometer (JPL/HVM) Instrument

The JPL/HVM measures the interplanetary magnetic field





Figs. 5 and 6. Two external views of the Pioneer 10 and 11 spacecraft.

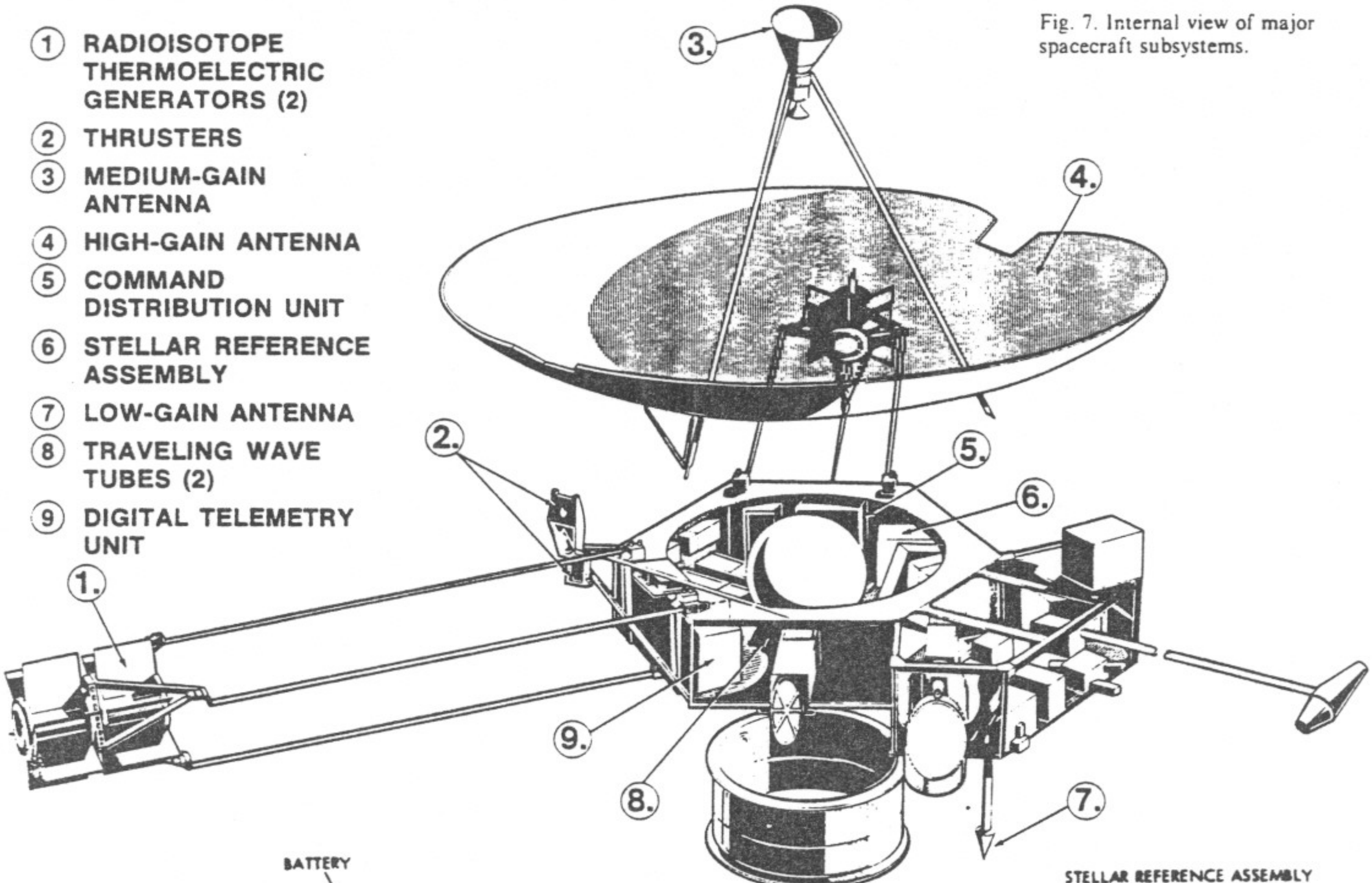


Fig. 7. Internal view of major spacecraft subsystems.

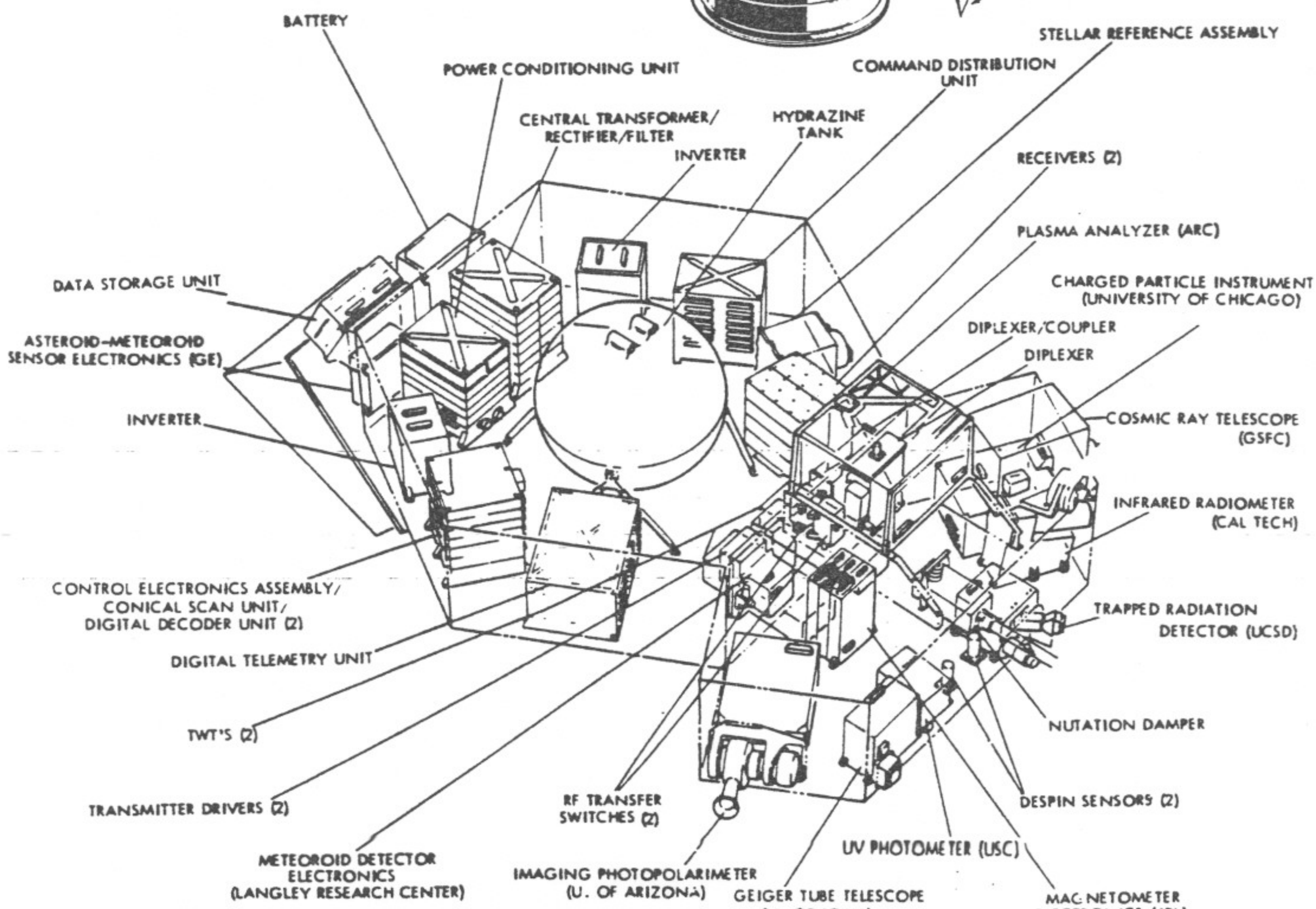


Fig. 8. Internal arrangement of spacecraft equipment compartment.

with high accuracy. A team led by Edward Smith at the Jet Propulsion Laboratory uses this instrument to measure the vector magnetic field point-by-point in the heliosphere. This experiment made the first *in situ* measurements of the planetary magnetic fields of Jupiter and Saturn and provided the basis for detailed models thereof. It also showed that the magnetic field at large distances from the Sun is dominated by large scale structures: co-rotating interaction regions and a current sheet which divides the solar field into two hemispheres. Ongoing efforts include: identification and analysis of discontinuities and shocks, the computation of power spectra in the interplanetary field fluctuations at large distances, and the observed properties of Alfven waves at large heliocentric distances. In addition, collaborative studies with energetic particle investigations involve: the acceleration of protons by co-rotating interplanetary shocks, the effect of co-rotating interaction regions on cosmic rays, and the relation between interplanetary protons, co-rotating interaction regions and waves.

The Pioneer 10/11 HVM is an advanced version of the Mariner 4 and 5 HVM instruments. The essential elements include a helium lamp, a circular polariser, a helium absorption cell, Helmholtz coils, a lens and an IR detector. The presence of an ambient magnetic field causes a sine wave modulation of the IR radiation passing through the gas cell at the fundamental frequency of the applied circular sweep field; nulling currents applied to cancel this field "signal" are the sensor outputs.

The instrument has the necessary sensitivity over the wide dynamic range needed to operate in the very weak interplanetary fields with selectable operating ranges from ± 4.0 gamma to ± 1.41 gauss. Fields smaller than 0.01 gamma can be detected.

The HVM has been productive throughout all phases of the Pioneer 11 Mission; but the HVM on Pioneer 10 failed one year after Jupiter encounter.

2.3.2 Plasma Analyser (ARC/PA) Instrument

A team led by Aaron Barnes at the Ames Research Center uses an electrostatic plasma analyser to measure the direction and energy of ions and electrons in the solar wind. This experiment discovered, measured and developed the first model of the bow shock and magnetosheaths of Jupiter and Saturn. It also conducted the first extensive survey of the solar wind at large distances, which showed a radial flow outward to 32 AU, the existence of solar flare events at such distances, and maintenance of higher temperatures in the plasma than adiabatic theory would predict. Present and future studies include: heliocentric distance dependence of solar wind parameters; correlation of results with solar activity and results from other spacecraft; identifying and studying a terminal shock (heliospheric boundary); heliocentric distance dependence and dynamics of the solar wind helium component; and velocity distribution functions of proton plasma data enabling study of the magnitude and occurrence of nonthermal components of the solar wind.

The instrument is an electrostatic energy per unit charge (e/q) spectrometer capable of measuring the flux as a function of E/q and incident direction of positive ions and electrons. The E/q of incoming particles is determined by the voltage across the instrument's quadrispherical analyser plates. These plates reject all but a narrow band in the incident particle spectrum.

This analyser system is capable of determining the incident plasma distribution parameters over the energy range of 100-18,000 eV for protons and approximately 1-500 eV for electrons. It covers the dynamic range for charged particle fluxes from approximately 1×10^{2} to 3×10^{9} $cm^{-1}s^{-1}$ and is capable of resolving proton temperatures down to at least 2×10^{3} K level.

The experiments continue to provide excellent data.

2.3.3 Charged Particle (UC/CPI) Instrument

John Simpson's group at the University of Chicago provided a charged particle detection instrument which measures the energy and composition of cosmic rays. This experiment discovered Jovian electrons escaping the magnetosphere of Jupiter and propagating throughout the Solar System. It also discovered an anomalous helium component in the cosmic rays which is the dominant ionic species in this energy range throughout the heliosphere.

Continuous measurements of the fluxes, energy spectra and chemical and isotopic composition of energetic charged particles in the interplanetary medium are being obtained. In particular, the instrument separately identifies individual nuclei, including protons and helium nuclei, through to the higher mass nuclei up to oxygen and measures the energy and differential flux of these particles over the range from 0.5 to 500 MeV/nucleon. The integral fluxes of nuclei with energies >500 MeV/nucleon from protons through iron are also measured. Electron spectra are measured from 3 to 30 MeV.

The University of Chicago's Charged Particle Instrument consists of four sensor systems: two multi-element telescopes, an electron current detector (ECD) for electrons greater than or equal to 3 MeV, and a fission cell for high-intensity, high-energy nucleon fluxes. The low-energy telescope (LET) contains a titanium window, a thin (37 micron) silicon detector, and electrically connected annular and flat silicon detectors. The main telescope contains seven detectors and complex logic circuitry, designed primarily for measurements of the interplanetary cosmic ray composition, flux and spectra.

The instrument continues to operate normally on both spacecraft.

2.3.4 Geiger Tube Telescope (UI/GTT) Instrument

James van Allen at the University of Iowa provided Geiger-Mueller tubes and solid state detectors which measure the intensity, energy spectra and angular distribution of energetic electrons and protons in the heliosphere. This experiment, together with the other energetic particle experiments, made the first *in situ* measurements of the energetic particle distribution in the magnetosphere of Jupiter. It also discovered and conducted the initial survey of Saturn's radiation belts and used particle absorption techniques to confirm the optical discovery of a new Saturnian satellite and other satellite and ring features.

The flight instrumentation utilises seven Geiger-Muellr er (GM) tubes as elementary detectors. Three tubes are arranged in an array to serve as a multi-function particle telescope. The axes of the three tubes are parallel to each other and to the X-Y plane of the spacecraft. The tubes are stacked one above the other to form a telescope for penetrating particles ($E_p >$ 70 MeV) moving approximately in the +Z or -Z (spacecraft rotational) axis direction. The useful dynamic range extends from 0.2 to 1×10^{6} counts per second for individual tubes and from 0.01 to 3×10^{4} counts per second for the coincidence conditions. Three other detectors are arranged in a triangular array and fully enclosed in a 7.2 g/cm^{-2} shield of lead to form a shower detector. Outputs are processed to compare individual primary events with secondary showers. A final detector is configured as a scatter detector, using a gold scatter target and a thin mica window, affording a 30° full angle view cone; it admits low-energy electrons ($E_e >$ 0.06 MeV) but discriminates against protons

($E_p > 20$ MeV).

The UI/GTT instrument has operated properly throughout the mission on both Pioneer 10 and 11.

2.3.5 Cosmic Ray Telescope (GSFC/CRT) Instrument

A team led by Frank McDonald at the Goddard Space Flight Center provided a set of cosmic ray telescopes which measure low, medium and high energy elements from hydrogen to neon. This experiment was the first to discover an anomalous oxygen and nitrogen component in the cosmic radiation and from these measurements developed a model for the interplanetary acceleration of high energy particles. It also measured the nature of the modulation of galactic cosmic rays by the solar wind.

The flight instrumentation consists of three solid state telescopes. The High Energy Telescope is a three-element linear array operating in two modes: penetrating and stopping. For penetrating particles, differential energy spectra are obtained for He and H_2 from 50-800 MeV/nucleon. The stopping particle mode covers the range from 22-50 MeV. The Low Energy Telescope I is a three-element linear array, responding to protons and heavier nuclei from three to 22 MeV/nucleon, and providing both energy spectra and angular distribution over this range. The Low Energy Telescope II, designed primarily to study solar radiation, is a three element linear array. The top detector will stop electrons in the 50-150 KeV range, and protons in the 50 KeV-3 MeV range. The second detector will respond to electrons in the interval 150 KeV-1 MeV and protons between three and 20 MeV. The third element serves as an anticoincidence guard.

The GSFC/CRT instrument has been active throughout the mission and continues nominal operation on both Pioneers 10 and 11.

2.3.6 Trapped Radiation Detector (UCSD/TRD) Instrument

R. Walker Fillius at the University of California at San Diego provided a Cerenkov detector which measures the gradient and transport properties of very high energy cosmic rays. It also provided a large body of high quality magnetospheric data at Jupiter and Saturn.

The Cerenkov detector counts galactic cosmic rays in the enrgy range above 500 MeV per nucleon, higher than the other on-board cosmic ray detectors. Also, it is directional, measuring anisotrophies perpendicular to the spacecraft spin axis. As a result, the radial gradient of the galactic cosmic rays, and their modulations caused by the solar radiation in interplanetary space are being observed. Additionally, another detector with an 80 MeV threshold is providing crosschecks with other instruments.

Of the four detector assemblies in the UCSD instrument, detectors C and M are presently active. Detector C is a non-focused Cerenkov counter for energetic electrons, using an alcohol mass enclosed in a plastic can as the radiator, optically coupled to a matched photo-multiplier tube. Detector M is an omnidirectional counter for high energy protons and minimum ionising particles, consisting of a solid state diode embedded in a shield.

These detectors continue to be productive on Pioneers 10 and 11.

3.2.7 Ultraviolet Photometer (USC/UV) Instrument

Darrell Judge at the University of Southern California provided an ultraviolet photometer that detects hydrogen and helium in both interplanetary and interstellar regions. This experiment made the first direct measurement of helium in the atmosphere of Jupiter and measured the H/He ratio in interplanetary space at great distances from the Sun where local effects do not dominate. Continuing measurements will provide:

(1) a relatively complete sky survey of UV emissions from B-type or earlier stars and data on the interstellar extinction coefficient;

(2) measures of the density of the interplanetary H and He gases at large solar distances; and

(3) heliosphere boundary data, including observations of UV emissions from neutral H and He, and emissions from the hot plasma at the heliosphere boundary.

The flight instrument is a two channel UV photometer operating in the 200-1400 Å range. Selection of wavelength is achieved by the use of a field of view limiter and the use of filters and sensors. An aluminium filter in conjuction with a channeltron sensor is used to provide Hydrogen Lyman-Alpha data at 1216 Å. A lithium fluoride target cathode with a second channeltron sensor provides Helium data at 584 Å. The field of view (FWHM) is 1.15° x 9.3°. The photometer optical axis is positioned at an angle of approximately 20° with respect to the spacecraft spin axis; consequently, the field of view swept out by the spin motion is an annular ring 40° in diameter that moves only with the small reorientations of the spacecraft's spin axis as it tracks the Earth.

The USC/UV instrument has been active throughout the mission and continues to operate normally on both craft.

2.3.8 Imaging Photopolarimetry Experiment

T. Gehrels at the University of Arizona and J. Weinberg at the University of Florida have an Imaging Photopolarimetry Experiment (IPP) that combines three investigations in the visible light range, sharing use of a single flight instrument. Zodiacal light mapping was conducted at intervals throughout the interplanetary flight to assess the quantity and distribution of particulate matter (interplanetary dust) in the Solar System, until the zodical light was no longer detectable above the background starlight. This occurred at the far edge of the asteroid belt (3.3 AU distant from the Sun). Measurements were made of brightness and polarisation of light over a wide range of scattering angles.

Continuing periodic measurements were made to map the brightness distribution of the background starlight without the interference of the zodiacal light. Observations to complete sky mapping of background starlight for use in astronomy data interpretations have just been completed.

The flight instrumentation for the Pioneer 10/11 UA/IPP is an imaging photopolarimeter, consisting of an optical telescope positioned relative to the spacecraft spin axis by a stepping motor, a beam-splitting optical prism, two sets of coupling and filtering optics, four channeltron detectors, signal processing, logic, control, interface and power circuitry, all contained in a single housing. The telescope, which protrudes from the side of the spacecraft equipment compartment, has a 2.5 cm aperture, 8.6 cm focal length and provides an image with an instantaneous field of view of 40 x 40 mrad for Zodiacal light studies. The Wollastron prism splits the image into two orthogonally polarised beams which are filtered to two colour channels: 3900-4900 Å (blue) and 5900-7000 Å (red). The imaging photopolarimeter was periodically active throughout most of the mission, but has been placed in standby mode pending evaluation of additional proposed observations.

2.3.9 Meteoroid Detector (LaRC/MD) Instrument

W. Kinard at NASA's Langley Research Center provided a Micro-Meteoroid Detector which makes *in situ* measurements of solid particle population in the 10^{-8} g mass range and larger using penetration cells attached to the exterior of the spacecraft. It measures flux levels, distribution and particle size, of meteoroids too small to detect readily by optical means, and has performed a preliminary study of the meteoroid penetration hazrad to future spacecraft traversing the asteroid belt. Pioneer 10 has characterised the distribution of the particles as small as 10^{-8} g to 22 AU, and Pioneer 11 followed with discrimination down to 10^{-7} g.

The flight instrumentation for the Pioneer 10/11 LaRC/MD consists of 12 banks of penetration cells, attached on standoffs to the spacecraft's exterior. Each bank is approximately 20.3 x 30.5 cm size, constructed like an air mattress, with 18 individual cells in each bank. Each cell contains a pressure-sensitive transducer and was filled with gas prior to sealing. Penetration by a particle causes a gradual pressure loss, with evacuation time ranging from a few seconds to as long as 30 minutes and longer in duration. The transducer detects this pressure loss as a critical pressure is reached and a plasma discharge takes place across the cell. These events are counted to indicate micro-meteoroid population.

The LaRC/MD instrument has been active from instrument power turn-on throughout the mission, out to approximately 22 AU. At this point, the temperature is about 53 K and the gas in the detector cells condenses. Thus, the Pioneer 10 MD has completed its performance, while Pioneer 11 MD will continue to provide data for some time.

2.3.10 Radiometric Science

John Anderson at the Jet Propulsion Laboratory uses accurate Doppler tracking of the spin stabilised spacecraft to search for differential gravitational forces from a possible trans-Neptunian planet and to search for gravitational radiation. This experiment determined the gravitational fields of the Jupiter and Saturn systems and developed the current model for these fields. It also discovered a 20% discrepancy in the mass of Io as determined by ground based telescopic measurements.

Residuals in optical measurements of planetary motions suggest to astronomers that at least one more massive "dark" planet remains to be found in the Solar System. In fact, a singular planet could strongly diminish all such residuals. An organised search has recently been proposed by astronomers in which intense astrometric observations of Neptune's position would be analysed to confirm the existence of, and locate, the suspected planet. The Pioneer 10/11 radio science Principal Investigator notes that his analysis of Pioneer data has distinctly greater sensitivity in a much shorter observation span than does the proposed optical data set. This concept is being pursued, beginning with an analysis of the Pioneers' sensitivity to the mass and general location of the candidate discovery.

Gravity waves from cataclysmic cosmic events might be detectable in the Doppler signal between Pioneer 10 and Earth. Pioneer 10 presents the most sensitive capability available to observationally confirm the existence of these waves, predicted by the General Theory of Relativity. Only Voyager 2, among existing or committed spacecraft, might eventually present a comparable capability with coherent two-way Doppler. Doppler data from Pioneers 10 and 11 is being searched whenever any of these spacecraft is near opposition with the Sun relative to Earth. In that circumstance, the solar wind's distortion of the Earth/spacecraft radio path is minimal, and the sequential wave effect upon the spacecraft and the Earth will be most apparent. Pioneer 10 obtained data for these preselected conditions in 1981, 1982 and 1983. These conditions provide a maximum sensitivity for gravitational waves with periods as long as three or four hours and with peak acceleration smaller than 1 mm s^{-2}.

These pricipal investigators and their team members represent 13 institutions and, along with NASA, study the basic problems of heliospheric and cosmic ray physics.

2.4 Exploring Our Heliosphere

The Pioneer spacecraft are now probing unexplored regions of deep space in order to investigate a new set of astrophysical problems. These spacecraft were first to chart a course through the Asteroid Belt, fly by the giant planets Jupiter and Saturn, and will now examine the outer regions of our heliosphere. This will be the first *in situ* measurement of the large-scale plasma and magnetic field structure of a type G star. The heliosphere is considered to be the plasma envelope of the Sun which extends from the solar corona out to interstellar medium, where it is decelerated by particles and magnetic field interaction. This distance is thought to be between 50 and 100 AU. In this section, we will describe some general properties of the Sun which is the source of the heliosphere, and then describe those parameters which will be investigated by the Pioneer missions.

2.4.1 General Properties of the Sun and Its Atmosphere

The Sun is a main sequence type G spectral class star on the Hertzsprung-Russell diagram with average mass and luminosity. The mass of gas is so large that the Sun's gravitational field compresses the gas to a density and temperature sufficient for nuclear fusion reactions to occur. Heat escapes from the central nuclear burning region by radiation, convection and circulation which act as a dynamo to produce the magnetic fields observed in all regions above the photosphere. X-rays produced by the nuclear reactions and radiatively transported to the outer layers of gas which is heated and expanded. The Sun's magnetic field affects the solar radiation and the transport of magnetised plasma, energy and angular momentum outward into all regions of the heliosphere. Observations in recent years have shown that the magnetic fields produce "coronal holes" which are the source of a large fraction of the solar wind. This wind has been extensively studies since 1961. Its plasma energy density exceeds that of the magnetic field and, consequently, the field is carried outward past all the known planets by the plasma. This solar wind energy density is only 10^{-7} that of the radiative energy density flowing outward in the corona. This flow has highly variable features superimposed upon a steady long-term component. The number of sunspots and solar flares exhibit an 11 year cycle and the magnetic field polarity changes every 22 years. Shorter period whole body oscillations in the solar atmosphere have also been observed which also involve the convection zone under the photosphere.

2.4.2 Properties of the Heliospheric Plasma and Magnetic Field to be Explored by Pioneer

The Sun has just passed through a maximum in sunspot activity and the magnetic field has changed polarity in its 22 year interval. The Pioneer and Voyager spacecraft are now in positions to make significant measurements of the large-scale structures and time dependent phenomena in the only *in situ* accessible stellar atmosphere. Our heliosphere is a huge region in the interstellar medium created by the outflow of magnetised, ionised gas from the Sun. This gas expands until its momentum flux is balanced by the pressure of the interstellar magnetic field and gas. Pioneer 10 is beyond all the nine known planets and has not detected this boundary with the interstellar medium.

The average structure of the heliosphere has been studied intensively during the last two decades and the data from many spacecraft have substantiated the model proposed by Parker in 1961. The main features are a magnetic field drawn out to form Archimedean spirals in the ecliptic plane and a dipole like asymmetry in the polar direction. The plasma has an average constant velocity of 430 km. s^{-1} after its transitions from subsonic to supersonic flow within a few solar radii from the photosphere. The density decreases as $6.5/R^2$ p+cm^{-3} where R is in AU and the magnetic field configuration in the ecliptic conforms to the Parker predicted Archimedian spiral angles to within 1°.

This average structure of the solar wind being measured by the Pioneers has superimposed upon it time-dependent variations caused by solar flares and other coronal activity. These time-dependent phenomena on the Sun produce high speed streams and magnetohydrodynamic shocks that have been measured and theoretically modelled. As the plasma expands out beyond a few AU, the fast and slow streams overtake one another forming interaction regions which co-rotate with the Sun. One of the major goals of the Pioneer missions is to measure these transient collisionless shocked regions and observe the acceleration of local solar wind particles and the deflection of high energy particles and galactic cosmic rays travelling through our heliosphere. In addition, a better understanding of these transient phenomena is required in order to more accurately model the transport of heat from the solar corona out into the distant region of the heliosphere. Pioneer measurements have shown that the plasma temperature falls off more slowly with distance than a simple adiabatic expansion theory would predict. A better understanding of the hydromagnetic waves and other plasma transients is required in order to model this important solar heat transport phenomenon.

2.4.3 *High Energy Particles in the Heliosphere*

The high energy charged particle experiments on board the Pioneer spacecraft have made major contributions to our understanding of the mechanisms for transport of solar and galactic cosmic rays through our heliosphere. Correlative measurements between Pioneer and both Earth-based and instruments orbiting at 1 AU are being used to observe the modulation of cosmic ray intensity, composition and spectral content produced by the magnetic fields and particles in the distant regions of the heliosphere. The energy range of the cosmic rays is so large that the length scale of the gyro radii span all the magnetohydrodynamic phenomena in the heliosphere. This permits the cosmic rays to be used as probes to examine the large scale electromagnetic features of the heliosphere, including a remote measurement of the boundary with the interstellar medium. Since the very high energy galactic cosmic rays enter the heliosphere from all directions with equal intensity, they can also be used to determine the shape of the heliospheric boundary if the modulation mechanism can be accurately modelled. Pioneer measurements obtained during the last decade have shown the existance of Jovian electrons that traverse most of the heliosphere, an amonalous helium component that is modulated with strong dependence on the solar magnetic field polarity, and high energy solar particles that are accelerated by shocks and co-rotating interaction regions. A complete set of particle and field measurements inside the heliosphere as the next solar minimum approaches may yield enough information for the modulation, acceleration and propagation models to be adquately developed in order to determine the size and shape of our heliosphere. One of the first indications that Pioneer has reached the boundary of the heliosphere may be the cessation of the 26 day rotation induced modulation of cosmic rays < 100 MeV/nucleon.

2.5 Interstellar Space

Both Pioneers also have an ultraviolet photometer that detects hydrogen and helium in both interplanetary and interstellar space. This experiment, operated by D. Judge at the University of Southern California, has measured the radial dependance of the UV glow out to 32 AU and analysis indicate an interstellar density of hydrogen to be 0.04 ± 0.01 cm^{-3} and helium to be 0.01 ± 0.002 cm^{-3}. This information is crucial for estimating the location of the heliospheric boundary.

Another experiment that is being conducted with both Pioneer 10 and 11 spin stabilised spacecraft, is an accurate Doppler tracking to search for differential gravitational forces from a possible trans-Neptunian planet and to search for gravitational radiation. John Anderson at the Jet Propulsion Laboratory has used this technqiue to accurately determine the gravitational fields of Jupiter and Saturn. This technique becomes more sensitive for detecting gravitational radiation and tidal forces as the distance between the Earth and spacecraft increases. Theoretical models [7] of gravitational radiation show that the intensity increases with lower frequencies.

The fundamental measurements inside the heliosphere and beyond in interstellar space make the Pioneer 10 and 11 missions two of the most exciting exploratory endeavours undertaken by NASA. Results obtained to date and anticipated in the future gives us a much clearer picture of the Sun as a star in our Galaxy.

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