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Paper Session II-C - Pioneer 10 Interstellar Studies

P. Dyal
Space Research Directorate NASA Ames Research Center

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Pioneer 10 and 11 Interstellar Studies

P. Dyal
Space Research Directorate
NASA Ames Research Center
Moffett Field, CA 94035

Abstract
The Pioneer 10 spacecraft may soon be the first man-made object to leave our solar system and penetrate the heliospheric boundary into interstellar space. Scientific investigators on this mission eagerly anticipate the opportunity to measure the physical processes occurring in the terminal boundary region and in the unexplored space known as the interstellar medium by astronomers who have studied it remotely with telescopes for many years. This paper is a descriptive overview of the Pioneer 10 mission and the dominant physical processes that have been discovered since its 1972 launch into our heliosphere and those processes that we expect to see at the boundary and in the interstellar medium.

Introduction
The Pioneer 10 spacecraft is now 53 astronomical units (AU) from the sun and is the farthest man-made object from the Earth. It, along with follow-on missions Pioneer 11, Voyager 1, and Voyager 2, are the only spacecraft now exploring the vast region of space called the “heliosphere.” This is the region of space around the sun where the solar wind plasma and magnetic field control the processes and physical state of the medium. The heliosphere extends from the sun out to interstellar space and theoretical models estimate the radius to be between 70 and 150 AU. The heliosphere is created by the expanding solar plasma which excludes the interstellar plasma and is subdivided into three regions: 1) the expanding solar wind, 2) a terminal shock produced by the back pressure of the interstellar wind upon the supersonic solar wind, and 3) the heliopause which forms the boundary between the solar plasma and the interstellar plasma. The properties of the interstellar plasma in the local neighborhood of the sun have been determined from radio and visible astronomical observations. Average values of the composition and physical state over many 1000’s AU have been calculated from theoretical models of the local interstellar medium (LISM). The only direct measurements to have been obtained are on galactic cosmic rays and interstellar neutral hydrogen and helium gas that penetrate our heliosphere. However, both the neutral gas and galactic cosmic rays are modified during their transit into the heliosphere. The Pioneer spacecraft has instruments onboard which measure the solar wind plasma, magnetic field, cosmic rays, and neutral hydrogen and helium atoms. The sensitivities of these instruments should allow measurements in all three regions of the heliosphere and in the local interstellar medium.

In addition to the intrinsic scientific interest in measuring the properties of the local interstellar medium, it is of practical interest to be able to predict the cosmic ray flux on and near the Earth. The heliosphere acts as a source of solar cosmic rays below ~100MeV/nucleon and completely shields us from the greatest number of galactic cosmic rays which are below this energy. The heliosphere significantly modifies the galactic cosmic ray spectrum from ~100MeV/nucleon to 1/GeV/nucleon and is transparent for higher energies. This along with the major new discoveries about the properties of the heliosphere as measured by the Pioneer and Voyager spacecraft indicate a need for an interstellar probe mission to conduct a detailed exploration of the new interstellar region beyond the heliopause boundary.

Pioneer Mission Description
Pioneer-Jupiter Project mission studies were initiated in the early 1960’s and came to fruition in 1969 when Ames Research Center was assigned the responsibility for this project. Three spacecraft were built; the first for testing, which is presently displayed in the National Air and Space Museum, the second was Pioneer 10 launched on March 2, 1972, and the third named Pioneer 11 was launched April 5, 1973. These two spacecraft were the first to be launched with enough energy to escape the solar system. The missions are expected to last three decades and the following objectives have evolved:

(1) Investigate the nature of the asteroid belt and assess its hazard to future missions.

(2) Explore the interplanetary medium beyond the orbit of Mars.
(3) Explore the environment of Jupiter.
(4) Explore the environment of Saturn.
(5) Explore the outer heliosphere.
(6) Explore the boundary of the heliosphere and the local interstellar medium.

Many individuals and institutions were required to implement these two missions. The Pioneer 10 and 11 Project was managed by Ames Research Center and NASA Headquarters, the Atlas Centaur booster by Lewis Research Center, launch operations by Kennedy Space Center, the Deep Space Network tracking by Jet Propulsion Laboratory (JPL), the radioisotope thermoelectric power generators by the Atomic Energy Commission, and the spacecraft was built by TRW Systems Group. Six universities and four NASA centers provided the scientific experiments for the project.

The Two spacecraft and most of the scientific instruments are in excellent condition. Data are being acquired on a daily basis at 16 bits per second with the 70-m diameter antennas of the Deep Space Network. This telemetry command and receiving capability should permit the spacecraft and experiments to be operated to the end of the century. At this time, the radioisotope power generator will only support the transmitter. In December 1991, Pioneer 10 was 53 AU from the sun and the round-trip light time was 14 hr 30 min. Pioneer 11 was 34.5 AU from the sun and the corresponding command and receive time was 9 hr 50 min.

Figure 1 shows 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 successfully performed on earlier missions. It has a thermally controlled equipment compartment with two sections, one is hexagonally shaped and contains electronic units and the propellant tank, and the other is a bay which contains 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 1.8m at 120° spacing. The RTGs are 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 maneuvers; 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/meteoroid detector.

The spacecraft is attitude-stabilized by spinning about an axis which is parallel to the axis of the 2.7-m reflector, the nominal spin rate for Pioneer 10 is 4.8 rpm. Pioneer 11 spins at approximately 7.8 rpm. During the mission, an Earth-pointing attitude is required. Periodic attitude adjustments are made throughout the mission to compensate for the variation in the heliocentric longitude of the Earth-spacecraft line. in addition, correction of launch vehicle injection errors were required to provide the desired Jupiter encounter trajectory and Saturn (Pioneer 11 only) encounter trajectory. These velocity vector adjustments involve reorientating the spacecraft to direction the thrust in the desired direction.

Thrusters are used to control the spin of the spacecraft, its attitude and its velocity, as shown in Figure 1. The precession maneuvers can be open-loop, for orientations toward or away from Earth-pointing, or closed-loop, for homing on the uplink radio frequency transmission from Earth.

For attitude control, a star sensor (Canopus) and two sunlight sensors provide reference, and three pairs of thrusters located near the rim of the antenna dish provide for orientation and roll maneuver. About 44.7 lb of hydrazine propellant remain on Pioneer 10 and about 11.3 lb remain on Pioneer 11 which is adequate to support the attitude control maneuvers well into the next century and will not limit the mission lifetime.

A unique characteristic of this spacecraft is the use of RTGs as the primary source of electrical power, making it independent of the sun. Each of the four space-proven SNAP-19 RTGs converts 5 to 6 percent of the heat released from plutonium dioxide.
radioactive decay to electrical power. The RTG lifetime is degraded at lower currents, therefore, voltage is regulated by shunt dissipation of excess power. At launch, the four RTGs supplied about 160 watts on each spacecraft. Examination of all subsystems on both spacecraft to date indicates that RTG power is the most critical in determining mission lifetime. Approximately 80 watts minimum are required to operate the spacecraft and a small subset of the scientific instruments. It is projected that Pioneer 11 will last until 1995 and Pioneer 10 until 2000 before the power drops to 80 watts. Presently some of the scientific instruments on Pioneer 10 and 11 are sequentially turned on and off to time-share the remaining power. The launch vehicle for Pioneer 10 and 11 was the three-stage Atlas/Centaur/TE-364-4 which boosted each spacecraft to begin the flight to Jupiter at about 51,680 km/hr. Pioneers 10 and 11 are proceeding in approximately opposite directions, the latter toward the nose of the heliosphere, and the former down the tail as shown in Figure 2. Both Voyager spacecraft are proceeding in the same quadrant of the solar system as Pioneer 11. These four spacecraft form a unique set of measurement probes to study the three-dimensional, large-scale structure of the heliosphere and, hopefully, enter the local interstellar medium. Pioneers 10 and 11 have asymptotic escape velocities from the solar system of 2.4 and 2.2 AU/yr, respectively.

Currently nine scientific experiments are being conducted on the two nearly identified spacecraft. A list of the experiments, principal investigators, and an abbreviated set of instrument properties is given in Table 1. References 1 and 2 give a more detailed description of the experiments and their operation during the early phases of the two missions.

**Heliospheric Properties**

The heliosphere is a very large bubble produced by the solar wind blowing outward against the interstellar plasma and magnetic field. The main constituent of the heliosphere is the magnetized solar plasma which not only excludes the interstellar plasma but also acts as a semitransparent and in some cases an opaque obstacle to the inward flow of other elements from the local interstellar medium such as cosmic rays, neutral gas, dust, and low frequency plasma waves. Figure 2 shows schematically the phenomenon and regions in this heliospheric bubble. Figures 3 and 4 show trajectories of the Pioneer and Voyager spacecraft. The interaction between the solar and interstellar plasma has been studied during the last three decades by investigators who still lead the theoretical efforts during this period of in situ spacecraft measurements (Ref 3, 4, 5, 6, 7). Many of the phenomena measured by the Pioneer spacecraft were predicted and adequately described by the above reference theoretical models, however, there is not presently a unanimous agreement on the distance to the boundary. Theoretically estimates vary between 70 and 150 AU due to uncertainties about the properties of the interstellar medium used to constrain the models. The heliospheric model shown in Figure 2 appears very similar to the Earth's magnetosphere since the solar system is moving through the local interstellar medium. The solar wind flows at supersonic speeds away from the sun and is slowed to subsonic speeds as it meets the interstellar medium and deflected downstream. The model predicts a terminal shock to occur in this region that will completely surround the solar system (Ref 7). After passing through the shock, the solar wind will curve away from the upstream direction and flow down the heliotail in the same direction as the interstellar flow. The boundary between the solar wind plasma and the interstellar plasma is the heliopause and the plasma will flow down the tail and eventually diffuse into the interstellar medium. The Pioneer 10 and 11 missions have significantly added to our understanding of this giant heliospheric region and the instruments have the sensitivity to measure the anticipated properties of the local interstellar medium.

Pioneer solar plasma measurements out to 50 AU show that the mean velocity is a constant ~430 km/sec, the mean density varies as \( r^{-2} \) with 10 p*/cm\(^3\) at 1 AU, and that the temperature decreases more slowly than \( r^{-3/2} \) (the adiabatic expansion). The later indicates local heating of protons throughout the heliosphere (Ref 8). The mean temperature at 1 AU is ~50,000°K. The solar wind evolves with time, radial distances, and longitude to produce two main types: transient and corotating. Corotating streams in the inner heliosphere at a distance from the sun of ~0.25 AU have a steep leading and trailing edge of plasma energy density, near 1 AU the corotating stream profiles have a gradual rise and a gradual decay, near 1.5 AU the gradual rise changes to two abrupt increase at a pair of shocks. Beyond ~10 AU, the corotating streams have merged to produce a single large compression region.

The magnetic field measurements on Pioneer agrees with the Parker model (Ref 4) in that \( B \propto \frac{1}{r} \) with a value of 5 nT at 1 AU and the field lines are drawn out by the solar plasma to form Archimedean spirals in the ecliptic plane and dipole-like asymmetry in the polar directions (Ref 9). These field measurements also established the physical origin of the sector structure to be a current sheet which separates the north and southward hemispheric fields of the sun. This current sheet has a wave-like structure and has a low or equatorial inclination at solar minimum and a high or meridional inclination at solar maximum. During every 11 year solar maximum, the solar dipolar field reverses direction and loses its primary dipolar character. Subsequently during approach to solar minimum, the
The heliospheric terminal shock and heliopause region.

In addition to the two main components (solar plasma and magnetic field) that govern the large scale structure of the heliosphere, there are two additional components that permeate the entire region; cosmic rays and neutral hydrogen and helium. These two components have origins both internal and external to the heliosphere. Measurements obtained in deep mines and on the Earth’s surface, in atmospheric balloons, and deep space missions indicate five main sources of cosmic rays; 1) solar cosmic rays, 2) the anomalous component, 3) charged particles accelerated at shocks in the solar wind plasma, 4) charged particles accelerated by planetary magnetospheres, and 5) galactic cosmic rays. Solar activity with characteristic 26 day, 11 year, and 22 year periods modulate the cosmic ray intensity and provide an excellent in-situ laboratory for spacecraft to study the heliosphere and to extend those results to regions that have not been penetrated by spacecraft. Charged particle acceleration models developed from measurements in the Earth’s magnetosphere permitted us to model acceleration in heliospheric corotating interaction regions and this in turn should permit more accurate acceleration models to be developed for galactic cosmic rays. The most intense flux of cosmic rays near 1 AU ever measured was produced by large solar flares. These ~ 100 MeV/nucleon bursts last for several days and consist mostly of protons. The August 1972 event had the potential to be a lethal hazard for astronauts performing tasks outside the shielding provided by their spacecraft. Studies of their high energy protons have provided an insight into the acceleration mechanism in the near vicinity of the sun.

The anomalous component of the cosmic rays were discovered in 1972 by the Pioneer spacecraft near 1 AU (Ref 10, 11). The presently accepted model (Ref 12) for the origin of the anomalous component starts with neutral atoms from the interstellar medium penetrating the heliosphere and becoming ionized by charge exchange with the solar wind or by the solar ultra-violet flux. After they are ionized the solar wind accelerates them to energies of ~10 MeV/nucleon. A study of these particles is leading to a better understanding of the acceleration mechanisms near the heliospheric terminal shock and heliopause region.

The cosmic rays that are produced in interplanetary shocks such as corotating interaction regions traveling by the Pioneer spacecraft provide information on the structure of the shocks and the acceleration mechanisms. These cosmic rays make up a considerable fraction of the low energy cosmic ray spectrum observed in the heliosphere. In addition, electrons which escape from Jupiter’s magnetosphere make up most of the high energy (~10 MeV) electron flux in the entire heliosphere. These Jovian electrons are intensity modulated at the 10 hour spin period of Jupiter and provide an excellent diagnostic tool for studying the interplanetary magnetic field.

The galactic cosmic rays that enter the heliosphere are significantly modified over the low energy part of their spectrum below ~1 GeV/nucleon. Above 1 GeV/nucleon the heliosphere is mostly transparent and the interstellar spectrum is directly observed by instruments on the Pioneer spacecraft. The modulation of the cosmic rays is produced by their interaction with the heliospheric magnetic field which is controlled by the sun. The 11 year and 22 year solar cycle variation in this magnetic field provide a useful tool for studying diffusion and drift models of cosmic ray modulation. This modulation process produces a positive radial gradient in the cosmic ray intensity which indicates that the intensity increases as the spacecraft is further from the sun. Measurements during solar minimum show a gradient of ~0.6%/AU and at solar maximum of ~1.4%/AU (Ref 13) indicating a modulation boundary at 70 AU and 150 AU where the interstellar flux level has been reached. The dynamic pressure of the solar wind is highest during solar minimum due to the more uniformly high speed plasma flows from the coronal holes that have drifted toward the equatorial regions on the sun. The anomalous components are modulated much more strongly than the galactic ray amounts. The helium flux at Pioneer 10 in 1987 was measured to be approximately 30 times that measured at Earth (Ref 14).

The Pioneer spacecraft also has an instrument to measure the abundance of neutral hydrogen and helium by observing the solar Lyman-alpha 1216Å and He 584Å photon that are backscattered from these neutral atoms (Ref 15). The Lyman-alpha intensity decreases approximately as I/R from the Earth to 50 AU. Deviations from this I/R dependence has been interpreted by investigators to indicate that the Pioneer 10 spacecraft is approaching the terminal shock (Ref 15). Most of the backscattered UV intensity originates from neutral hydrogen and helium that penetrates the heliosphere and is unimpeded by the large scale magnetic field. Some of the atoms are ionized by either charge exchange with solar wind protons or photoionization by solar UV radiation which produces a slight variation in the neutral atom density at the heliospheric termination shock and a large decrease near the sun.
Local Interstellar Medium Properties

If the Pioneer spacecraft continue to operate long enough to travel through the heliopause region produced by the solar plasma interacting with the local interstellar plasma, then a first in-situ measurement of the medium between stars can be obtained. The location of the heliopause boundary is very dependent upon the properties of the interstellar medium within 1000 AU of the sun. In particular, the gas species density, temperature, ion density, velocity, and magnetic field. The properties have only been measured by earth based telescopic observations which are less accurate than in-situ measurements by spacecraft in very localized regions. These inaccuracies dominate the uncertainties in determining the distance from the sun to the heliospheric outer boundary. An overview of the characteristics of the local interstellar medium has been published by Frisch (Ref 16).

The composition and density of the gas has been determined by measuring the characteristic spectral absorption lines of H°, C°, N°, Na°, Mg+, Fe+, AV°, and Zn+ in nearby interstellar clouds. Hydrogen is by far the most abundant species and its average spatial density is approximately 0.1H°/cm³. However the data shows that there is an asymmetrical distribution of interstellar gas surrounding the sun with more of the material on the galactic center side of the sun.

The temperature of the interstellar gas is measured by observing the thermal broadening of spectral lines with the Copernicus satellite (Ref 17). The average value of many of the trace elements is 11,750±750K. If the gas is in thermal equilibrium then the ion density is ~6% of the total gas density.

Both optical and UV absorption line data have been used to determine the velocity structure of the local interstellar medium to be -12 km/sec in the direction of 354° galactic longitude, +3° latitude. The sun is moving through this medium with a velocity of 20 km/sec toward galactic coordinate 57° longitude, +22° latitude. This coordinate system is at rest with respect to the average motion of stars near the sun which are orbiting around the center of the galaxy.

The magnetic field is estimated by observing the dispersion and Faraday rotation of pulsar signals (Ref 18). The measurement combines the effect of electron density and the parallel component of the magnetic field and the results are consistent with a magnetic field of ~0.5 nT.

The external pressure exerted by the interstellar medium upon the heliosphere is a function of the flowing interstellar plasma and magnetic field. For the interstellar parameters described above: 0.006 ions/cm³ and B=0.5nT, the heliospheric termination radius would be ~100 AU.

Summary

The Pioneer 10 spacecraft radioisotope power supply will permit the onboard instruments to operate out to approximately 80 AU. Subsequently, the spacecraft transmitter will continue to permit tracking the S band signal out to approximately 120 AU. This should place the spacecraft well into the heliopause and possibly into the local interstellar medium. After this time ~2015AD, the spacecraft will continue to proceed at a velocity of 2.4 AU/yr toward galactic longitude 82.8°, latitude 2.9° as shown in Figure 5. The nearest start to the sun is Proxima Centauri (part of the Alpha Centauri triple system) and Pioneer 10 will approach within 390,000 AU in approximately 26,000 years from launch.

References


<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detection Principle</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Helium Vector Magnetometer</td>
<td>Helium vapor; Zeeman effect</td>
<td>0.01 gamma; range ±4.0 gamma to ±1.41 gauss</td>
</tr>
<tr>
<td>Dr. Edward J. Smith</td>
<td></td>
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<tr>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>2. Plasma Analyzer</td>
<td>Electrostatic analyzer; channeltrons</td>
<td>0.1 to 18 KeV protons, 0.001 to 0.5 KeV electrons; 10^2 to 10^9P+cm^{-2}sec^{-1}</td>
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<tr>
<td>Dr. Aaron Barnes</td>
<td></td>
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<tr>
<td>Ames Research Center</td>
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<tr>
<td>3. Charged Particle Instrument</td>
<td>Two Si detector multi-element telescopes electron detector and fission cell</td>
<td>Discriminates protons through oxygen; 0.5 to 500 MeV/nucleon; electrons 3 to 30 MeV; integral fluxes for P^+ through Fe^+ &gt;500 MeV/nucleon</td>
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<tr>
<td>Dr. John A. Simpson</td>
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<td></td>
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<tr>
<td>University of Chicago</td>
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<td></td>
</tr>
<tr>
<td>4. Cosmic Ray Telescope</td>
<td>Three Si solid state telescopes</td>
<td>1) P^+ to Ne; 3 to 22 MeV/nucleon</td>
</tr>
<tr>
<td>Dr. Frank B. McDonald</td>
<td></td>
<td>2) Electrons 0.5 to 1.0 MeV; P^+ 0.05 to 20 MeV</td>
</tr>
<tr>
<td>University of Maryland</td>
<td></td>
<td>3) P^+ and He; 22 to 800 MeV/nucleon</td>
</tr>
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<td>5. Geiger Tube Telescope</td>
<td>Geiger-Mueller tubes, Si solid-state detectors</td>
<td>P^+ &gt;70 MeV; 0.2 to 10^6 counts/sec; e^- &gt;0.06 MeV; P^+ 0.6 to 3.4 MeV</td>
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<tr>
<td>Dr. James A. Van Allen</td>
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<td>University of Iowa</td>
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<tr>
<td>6. Trapped Radiation Detector</td>
<td>Cerenkov detector; alcohol</td>
<td>e^- 0.5 to 12 MeV; P^+ &gt;80 MeV; Z^+ &gt;500 MeV/nucleon</td>
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<td>University of California, San Diego</td>
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<tr>
<td>7. Ultraviolet Photometer</td>
<td>A1 filter with channeltron for hydrogen Lyman alpha and LiF target cathode for 584Å helium</td>
<td>200 to 1400 Å; field of view 1.15° x 9.3° H and He lines at 1216Å and 584Å</td>
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<tr>
<td>Dr. Darrell L. Judge</td>
<td></td>
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<tr>
<td>University of Southern California</td>
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<td>8. Celestial Mechanics</td>
<td>Doppler tracking of spacecraft at 2110 MHz uplink and 2292 MHz downlink</td>
<td>Acceleration &gt;1 mm/sec^2</td>
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<tr>
<td>Dr. John D. Anderson</td>
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<td></td>
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<td>Jet Propulsion Laboratory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Imaging Photopolarimeter</td>
<td>2.54 cm Maksutov telescope</td>
<td>Field of view 0.028° square, red and blue filters. 64 shades of gray. Used spacecraft spin for scanning.</td>
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<tr>
<td>Dr. Tom Gehrels</td>
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<tr>
<td>University of Arizona, Tucson</td>
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Fig. 1. Pioneer/Jupiter spacecraft.
OUTER BOUNDARY OF HELIOSPHERE

SUBSONIC FLOW

SHOCK TERMINATING THE REGION OF SUPersonic SOLAR WIND

INTERSTELLAR WIND

INTERSTELLAR BOW SHOCK (?)

Figure 2
Fig. 3. Trajectories of Pioneer 10 and 11, and Voyager 1 and 2.
1. Proxima Centauri
2. Ross 248
3. Lamda Serpens
4. G 96
5. Altair
6. G 181
7. G 838
8. D +19 5036
9. G 172.1
10. D +25 1496

Pioneer 10 closest approach to selected stars during the next 862,064 years.

Figure 5
Near Star Encounters for Pioneer 10