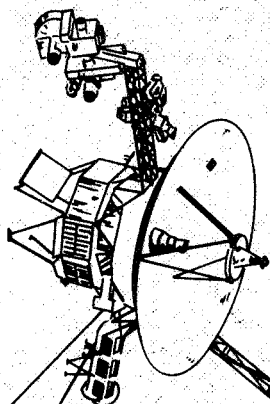


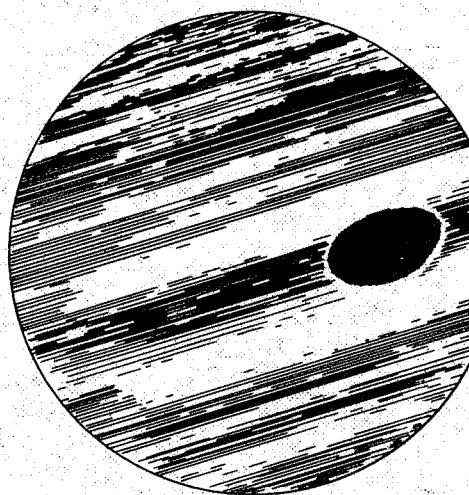
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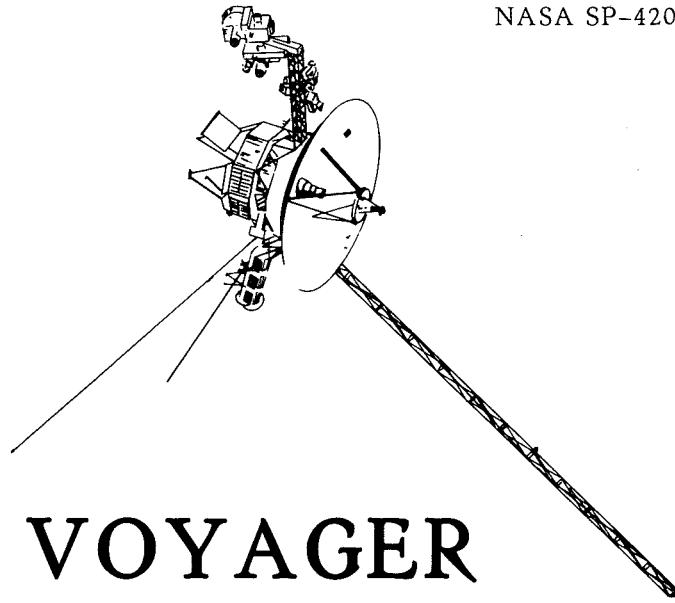
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VOYAGER TO JUPITER AND SATURN

National
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VOYAGER TO JUPITER AND SATURN



Scientific and Technical Information Office 1977
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

For sale by the National Technical Information Service
Springfield, Virginia 22151

Foreword

THIS publication briefly describes the National Aeronautics and Space Administration's Voyager mission to explore the giant planets of the outer solar system—Jupiter, Saturn, and possibly Uranus. Our Pioneer 10 and 11 missions to Jupiter have already given us a brief glimpse of the majesty of that giant planet and its satellites. Based on that reconnaissance, the two Voyager spacecraft will now explore in more depth the characteristics of the Jovian system and make the first concerted reconnaissance of Saturn, its satellites and mysterious rings. If all goes well, we may get our first close look at Uranus almost eight years from now, extending man's presence nearer to the edge of our solar system. Just as Voyager is building upon results from Pioneers 10 and 11, these missions in turn will pave the way for orbital and atmospheric-probe explorations in the 1980s.

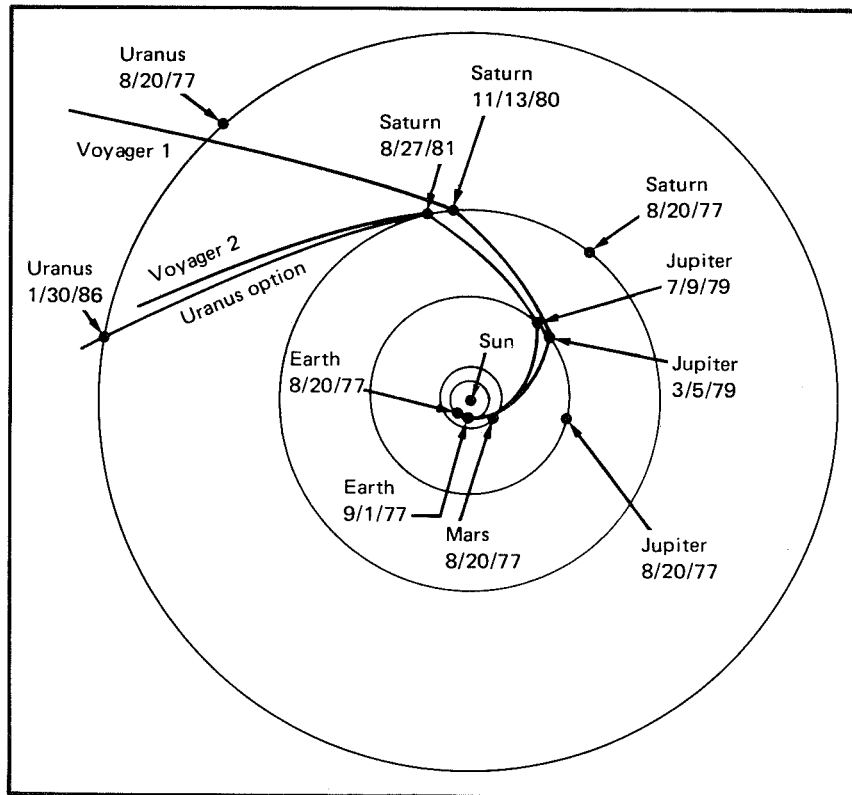
Voyager is an important incremental and sequential step in mankind's quest for knowledge about himself and his place in the universe. By comparing the outer planetary systems with each other, and with the terrestrial planets Earth (and its Moon), Mars, Venus, and Mercury, we will better understand how the solar system was formed, how it evolves, how life originated, and how the planetary environments are affected by the Sun.

NOEL W. HINNERS
*Associate Administrator
for Space Science*

June 21, 1977

Contents

	<i>Page</i>
THE VOYAGER MISSION	1
THE VOYAGER SPACECRAFT AND ITS INVESTIGATIONS.....	15
The Mission Module	15
Imaging Science Investigation	22
Infrared Radiation Investigation	26
Photopolarimetry Investigation.....	29
Ultraviolet Spectroscopy Investigation.....	31
Radio Science Investigation.....	34
Cosmic Ray Particles Investigation.....	37
Low-Energy Charged Particle Investigation	39
Plasma Particles Investigation.....	42
Magnetic Fields Investigation	45
Plasma Wave Investigation.....	47
Planetary Radio Astronomy Investigation.....	50
Appendix A—VOYAGER SCIENCE TEAMS.....	53
Appendix B—VOYAGER MANAGEMENT TEAM	57



VOYAGER TRAJECTORIES

The Voyager Mission

WHEN the first of two Voyager spacecraft approaches Saturn in November 1980, it will already be an experienced interplanetary explorer. An extremely busy encounter with Jupiter and its satellite system will be behind it, and more than three years of cruise observations. A twin spacecraft will have reported its own observations of the Jupiter system four months after the first. The scientists of the eleven Voyager investigating teams will have begun analyzing the mass of data acquired during the Jupiter encounters, and will be braced for the coming flood of observations from Saturn. A preliminary peek at Saturn from the Pioneer 11 flyby in September 1979 will have further whetted their anticipation and, perhaps, suggested last-minute changes in encounter plans. It will be an exciting time.

The two Voyagers will have been launched from Cape Canaveral years before, in August and September of 1977. Each will have taken advantage of the moving Jupiter gravity field to get a free ride to Saturn. One Voyager will pass by Jupiter at a distance of 130 000 km (nearly five times the planet's radius) on March 5, 1979, and go on to pass by Saturn at about three Saturn radii on November 13, 1980. The other Voyager will travel at a more leisurely pace. Its encounter with Jupiter on July 9, 1979, at a distance of ten Jupiter radii will boost it into a trajectory that will reach Saturn in August 1981. That's not all. The circumstances of its encounter with Saturn are flexible enough to maintain the option of a second gravity-assisted boost that would bring it to Uranus early in 1986. Theoretically, we might even repeat the trick at Uranus and send the spacecraft on to a 1989 rendezvous with Neptune. Table 1 gives comparative data for Jupiter and Saturn and the respective satellites that will be investigated by the Voyagers.

The emphasis of the Voyager missions is on comparative studies of the Jupiter and Saturn planetary systems. Each spacecraft will use identical sets of instruments to observe several satellites and the parent planet in each system: their body and surface characteristics,

Table 1.—*Comparative Data for Jovian and Saturnian Satellites*

Planet	Satellite	Diameter, km	Distance from Sun, 10 ⁶ km	Distance from planet, 10 ³ km	Period of orbit
Earth	—	12 756	149.6	—	1 yr
	Moon	3476	—	384.4	27.32 days
Jupiter	—	142 800	778.4	—	11.86 yr
	Amalthea	240	—	181.3	.49 day
	Io	3640	—	421.6	1.77 days
	Europa	3050	—	670.9	3.55 days
	Ganymede	5270	—	1 070	7.16 days
	Callisto	5000	—	1 880	16.69 days
	Leda	2 to 14	—	11 110	240 days
	Himalia	170	—	11 470	251 days
	Lysithea	6 to 32	—	11 710	260 days
	Elara	80	—	11 740	260 days
	Ananke	6 to 28	—	20 700	617 days
	Carme	8 to 40	—	22 350	692 days
	Pasiphae	8 to 46	—	23 300	735 days
	Sinope	6 to 36	—	23 700	758 days
	—	120 000	1424.6	—	29.46 yr
Saturn	Janus	?	—	168.7	.82 day
	Mimas	400	—	185.8	.94 day
	Enceladus	550	—	238.3	1.37 days
	Tethys	1200	—	294.9	1.89 days
	Dione	1150	—	377.9	2.74 days
	Rhea	1450	—	527.6	4.52 days
	Titan	5800	—	1 222.6	15.95 days
	Hyperion	160 to 920	—	1 484.1	21.28 days
	Iapetus	1800	—	3 562.9	79.33 days
	Phoebe	60 to 320	—	12 960	550.45 days

their atmospheres, and environments. The journey from Earth to Saturn provides the opportunity to explore the interplanetary medium at distances from 1 AU (the mean radius of the Earth's orbit) to 10 AU. After leaving Saturn, the two spacecraft are likely to continue sending data from distances as much as 20 AU or more.

Successive planetary encounters by two identically instrumented spacecraft make it possible to examine some of the bodies under different illumination and observation angles, and to study changes

in their atmospheres. During most of their flights both spacecraft will be located at different distances from the Sun. Comparing the arrival times of solar-wind disturbances will let us calculate the speed at which these events travel through interplanetary space.

Perhaps the most exciting objective of the missions is to learn more about those mysterious rings that have made Saturn such an object of wonder and curiosity for centuries.

Launch and Near-Earth Phases

The Voyagers will start their journeys from Launch Complex 41 at Cape Canaveral. The launch vehicle is the Titan IIIE/Centaur (fig. 1). Since it can't supply enough energy by itself to send the spacecraft off to Jupiter, the extra increment of energy is supplied by a solid rocket which, although it functions as a fifth launch vehicle stage, actually constitutes the spacecraft's Propulsion Module.

The Voyager spacecraft will leave Earth orbit at a higher velocity than any previous spacecraft. It will pass the Moon's orbit in 10 hours; it took Apollo astronauts (though moving many times faster than a rifle bullet) three days to get that far. The scientific instruments aboard the spacecraft will conduct observations of Earth and Moon for a few days, to check out and calibrate the instruments, and to provide a base line for the Jupiter and Saturn encounters.

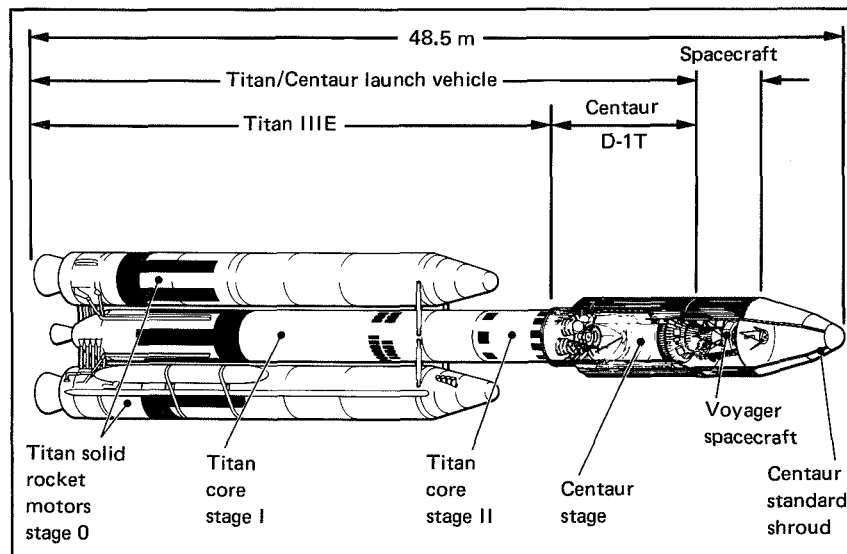


Figure 1.—Titan IIIE/Centaur launch vehicle with Voyager spacecraft.

Earth-Jupiter Cruise Phase

About 10 days after launch, the spacecraft and the mission operators and scientific investigators back on Earth will settle down to cruise routine. Most of the time, only the experiments that measure the fields and particles of interplanetary space will be operating regularly. Periodically, the pace of activity will be stepped up to conduct maneuvers recording measurements in all directions of the sky. The spacecraft will spin slowly about its Earth-pointing axis, meanwhile stepping its Science Scan Platform so that the remote-sensing instruments can survey the entire celestial sphere. These science maneuvers will occur each time the distance from the Sun increases by 0.5 AU, which will be about every other month. Several trajectory correction maneuvers during cruise will cancel launch injection errors and refine the aiming point for Jupiter.

The mission plan takes no particular notice of the asteroid belt that lies between 2.2 and 3.5 AU, beyond Mars' orbit. Until a few years ago there were speculations that a heavy concentration of small meteoroids in this belt might pose a hazard to spacecraft. However, the results of the micrometeoroid experiments on the Pioneer 10 and 11 missions showed no concentration within the belt, and the Voyagers are expected to fly serenely through.

Jupiter Encounter Phase

Eighty days before the closest approach to Jupiter, the remote sensing instruments will begin to observe the planet from about 80 million kilometers out. At that distance, with Jupiter covering about 1/10 degree in the field of the narrow-angle television camera, the images should be superior to the full-disk images made through telescopes on Earth.

Over the next seven weeks or so, the narrow-angle camera will record hundreds of images of Jupiter through all of its color filters, and the infrared and ultraviolet spectrometers and the photopolarimeter will begin their whole-planet observations. In addition, the latter two instruments will scan the orbits of the large satellites for evidence of clouds of ions. (Such clouds are believed to be spread out along the orbit of one satellite, Io.)

A month before closest approach, with Jupiter about 30 million kilometers away, the spacecraft will begin transmitting steadily at the encounter data rate. The three Deep Space Network receiving stations with 64-meter antennas will provide full-time coverage. The

various fields and particles experiments will go into their encounter modes, to observe the transition from the region dominated by the solar wind to Jupiter's magnetosphere.

Just before Jupiter fills the field of view of the narrow-angle camera, the imaging system will take what amounts to a time-lapse color movie, with an image every 9 minutes through 10 revolutions of the planet. Somewhat later, the camera will photograph the star field from known Scan Platform orientations to permit optical navigation. The final pre-encounter trajectory correction maneuver, 10 days before closest approach, will be based on the optical navigation data. After that, the narrow-angle camera will follow selected clouds and storm features of the Jovian atmosphere, and the spectrometers will scan across the atmosphere to determine the composition of the cloud bands.

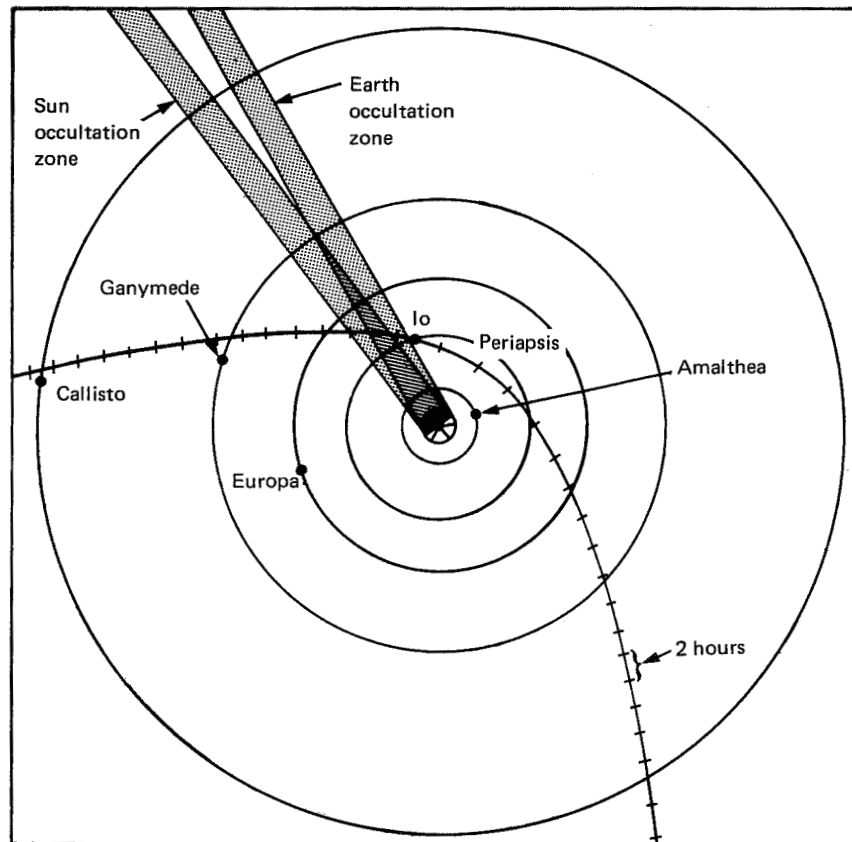
The busiest period of the entire mission will be the 48 hours centered on closest approach. For the earlier-arriving Voyager spacecraft, this will occur on March 5, 1979. Figure 2 illustrates the geometry of this first encounter, as projected onto Jupiter's equatorial plane. The concentric circles in the drawing are the orbits of the tiny innermost satellite, Amalthea, and of the four very large satellites first seen by Galileo: Io, Europa, Ganymede, and Callisto.

The spacecraft's track, which is marked off in 2-hour increments, enters at the lower right. Although it will cross the orbit of Callisto about 30 hours before periapsis, it will not photograph the satellite at that time. In fact, the closest encounter with all of the satellites except Amalthea will take place on the outbound leg.

On the inbound leg, the imaging system will be largely occupied with selected regions of Jupiter. For example, figure 3 shows the planned high-resolution coverage of the atmosphere in the vicinity of the Great Red Spot during one 3-hour period. As the spacecraft swings around the rapidly rotating planet, features that were imaged during the approach at very low phase angles (i.e., very nearly from the Sun's direction) will be imaged again at increasing phase angles until the Sun sets on them.

Returning to figure 1, we see that at periapsis (closest approach) the spacecraft will be 4.9 Jupiter radii (one radius at the equator is 71 600 km) from the planet's center. The giant planet's gravitational pull will whip the Voyager around behind it, imparting a large increase in velocity.

The moment when a spacecraft disappears behind a planetary body is a dramatic one for people in space flight operations. If the



Launch date: September 1, 1977
Jupiter arrival date: March 5, 1979

<i>Satellite</i>	<i>Flyby distance (km)</i>
Amalthea	440 000
Io	25 000
Europa	750 000
Ganymede	130 000
Callisto	130 000

Figure 2.—Voyager 1 encounter at 4.9 Jupiter radii. (View is normal to equator of Jupiter; position shown for each satellite is point of closest approach by Voyager.)

occluding body has no atmosphere, the cutoff of the steady stream of radio signals from the spacecraft is as sudden and startling as a thunderclap. Conversely, an Earth occultation by a planet like Jupiter, with a deep, dense atmosphere, provides an excellent

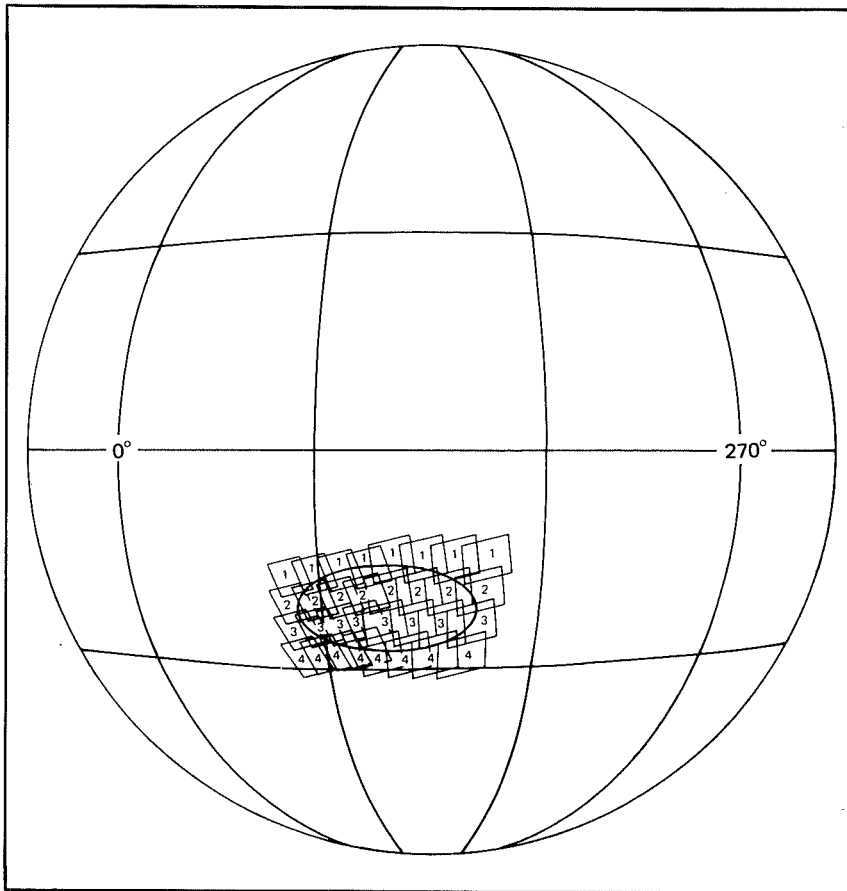


Figure 3.—Imaging frames of Jupiter's Red Spot to be obtained at closest approach.

opportunity to study the structure of the atmosphere and ionosphere through the refraction of radio waves.

Before Voyager enters Earth occultation, it will encounter the satellite Io at the very close range of 25 000 km. Io, the innermost of the Four Galilean satellites, is fascinating scientifically, with a number of remarkable features including Io's extraordinarily high reflectivity, and the toroidal cloud marking Io's orbit. The spacecraft will pass between Jupiter and Io, crossing the magnetic lines of force that seem, at times, to form an electrical pathway between the two bodies.

Before the spacecraft emerges from Earth occultation, it will enter Jupiter's shadow. This Sun occultation provides an opportuni-

ty for the ultraviolet spectrometer experiment to measure the composition of the upper layers of Jupiter's atmosphere. Meanwhile spacecraft cameras will take long exposures of the planet's night side in search of very bright meteors, lightning, and auroral discharges.

The Earth and Sun occultations do not pose any particular operational problems for the mission. Scientific data taken during Earth occultation will be recorded for later transmission. Since the spacecraft depends on radioisotope generators rather than solar energy for power, it will not lose power during the solar eclipse.

During the next 24 hours, the spacecraft will make its closest approach to the other three Galilean satellites: Europa, Ganymede, and Callisto. Although Europa and Ganymede are to be seen at much shorter range by the second Voyager spacecraft, the difference in phase angle between the two sets of encounters makes all the satellite imagery scientifically valuable.

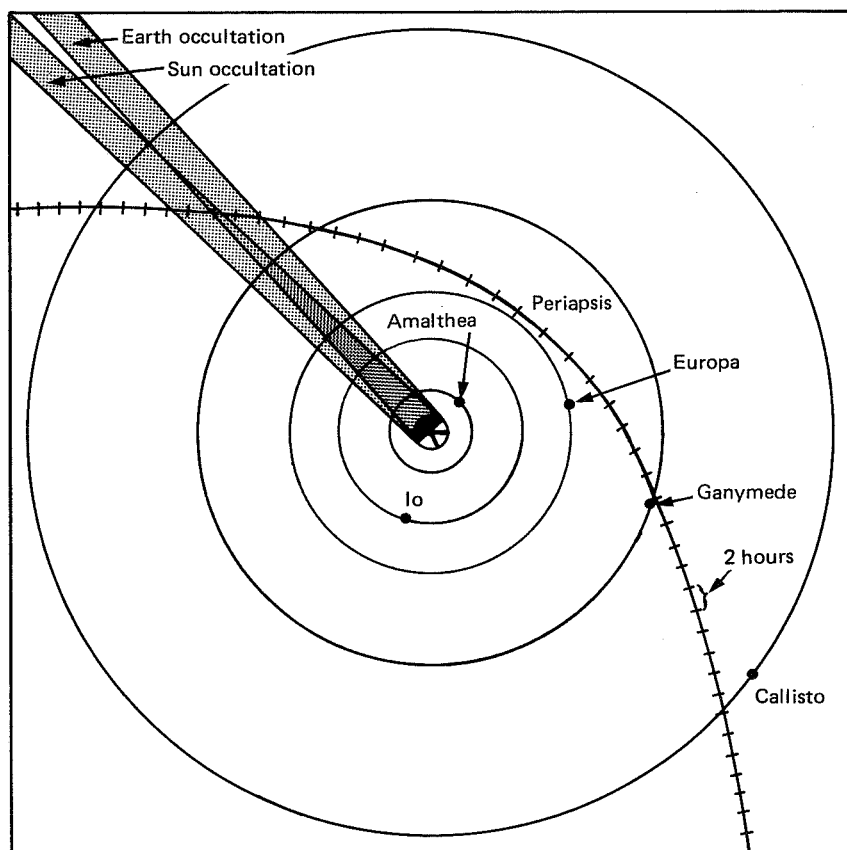
The first Voyager will recede from Jupiter at about a million kilometers a day as it coasts toward its rendezvous with Saturn. Its passage through the magnetosphere's extended tail makes it desirable to operate the fields and particles experiments at encounter rates for another 40 days. During that time there will be another trajectory correction maneuver, based on both optical and radio navigation.

Second Jupiter Encounter

The second Voyager will fly by Jupiter on July 9, 1979. The beginning of its encounter phase activities in mid-April will come just as its predecessor is settling down into the cruise mode. As far as scientific investigations are concerned, the Jupiter system will be under nearly continuous intensive observation for an eight-month period.

Figure 4 illustrates the geometry of the second Jupiter encounter. This time the closest approach will be 10 Jupiter radii, which is just outside the orbit of Europa. Callisto, Ganymede, Europa, and Amalthea will all be encountered on the inbound leg. The Ganymede encounter will be at the close range of about 50 000 km, providing image resolution about as fine as the very best telescope photographs of the Moon from Earth. Only Io will be too far to be observed at all.

Since the path of the second Voyager will not be as sharply curved by Jupiter's gravity, the Earth and Sun occultations will take



Launch date: August 20, 1977
 Jupiter arrival date: July 9, 1979

<i>Satellite</i>	<i>Flyby distance (km)</i>
Callisto	240 000
Ganymede	50 000
Europa	190 000
Amalthea	550 000

Figure 4.—Voyager 2 encounter at 10 Jupiter radii.

place at much greater distances from the planet. This will permit the grazing radio waves (and then the grazing ultraviolet rays) to explore new regions of the Jovian atmosphere.

As this Voyager recedes from Jupiter it, too, will see a crescent planet, and will perform remote sensing observations of features in the vicinity of the sunrise terminator.

Jupiter-Saturn Cruise Phase

During the period from the summer of 1979 to the autumn of 1980, both spacecraft will be operating in the cruise mode. As they proceed in turn from Jupiter's 5.2 AU orbit out to Saturn's 9.5 AU orbit, they will observe gradual changes in the character and temperature of the solar wind, and probably in the cosmic ray environment. The sky survey science maneuvers will continue at intervals of about 0.5 AU. The planetary radio astronomy experiment will increasingly be in a position to receive any radio emissions from Saturn.

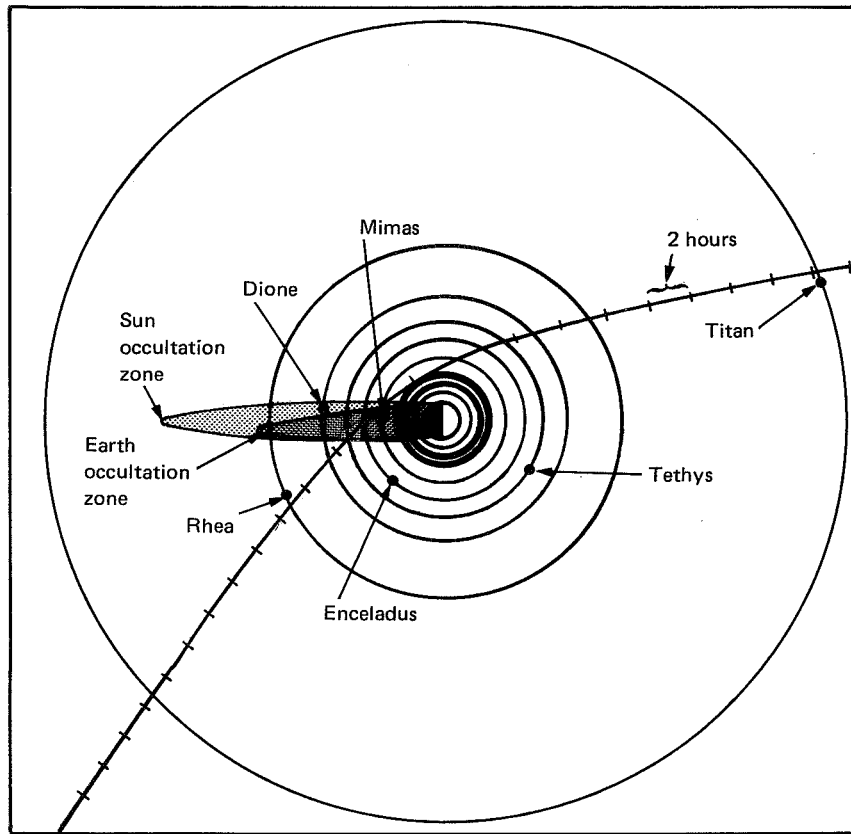
As the Earth proceeds along its orbit, there will be an annual solar conjunction for each spacecraft, during which radio signals will have to traverse the solar corona. Although the conjunctions will temporarily interfere with communications, they will provide opportunities for the measurement of coronal electron densities.

First Saturn Encounter

The Voyager that flew by Jupiter four months ahead of its twin will have widened its lead to nine months by the time it approaches Saturn. Toward the end of August 1980, the encounter phase will begin with the imaging of the planet and its rings from a distance of 96 million kilometers. The fields and particles experiments will go to encounter mode in mid-October, in order to determine the extent of the magnetosphere. By late October, the rings will be too large for the narrow-angle camera, and will be imaged in segments. Because the data rate that must be used at Saturn's distance is considerably less than that from Jupiter, most images will have to be recorded before transmission. (It will take about 1½ hours for radio signals to reach Earth.)

Figure 5 shows the geometry of the Saturn encounter. The day before closest approach, the Voyager will fly past the giant satellite Titan at a range of only 4000 km. The known facts and speculations about Titan's dense, hydrocarbon-laden atmosphere make it an exceptionally important object to study. The flyby of Titan will include an occultation from the Earth and the Sun, permitting good measurements of the atmosphere's composition and density.

On November 12, 1980, the spacecraft will fly past Saturn's southern hemisphere at a distance of 3.3 Saturn radii (about 200 000 km) from the center of the planet. Shortly afterward it will be occulted from the Earth by the rings, and then by the



Launch date: September 1, 1977

Saturn arrival date: November 12, 1980

<i>Satellite</i>	<i>Flyby distance (km)</i>
Titan	4 000
Tethys	410 000
Mimas	100 000
Enceladus	230 000
Dione	140 000
Rhea	60 000

Figure 5.—Voyager 1 encounter at 3.3 Saturn radii.

planet. Painstaking analysis of the received radio signal will provide a profile of the outer portion of Saturn's atmosphere as well as data on the rings.

After the flyby, the Voyager will examine four more satellites: Mimas, Enceladus, and Dione at distances from 100 000 to 250 000

km, and finally Rhea at 60 000 km. Then for another month the instruments will look back at the crescent planet and its tilted rings.

Second Saturn Encounter and the Uranus Option

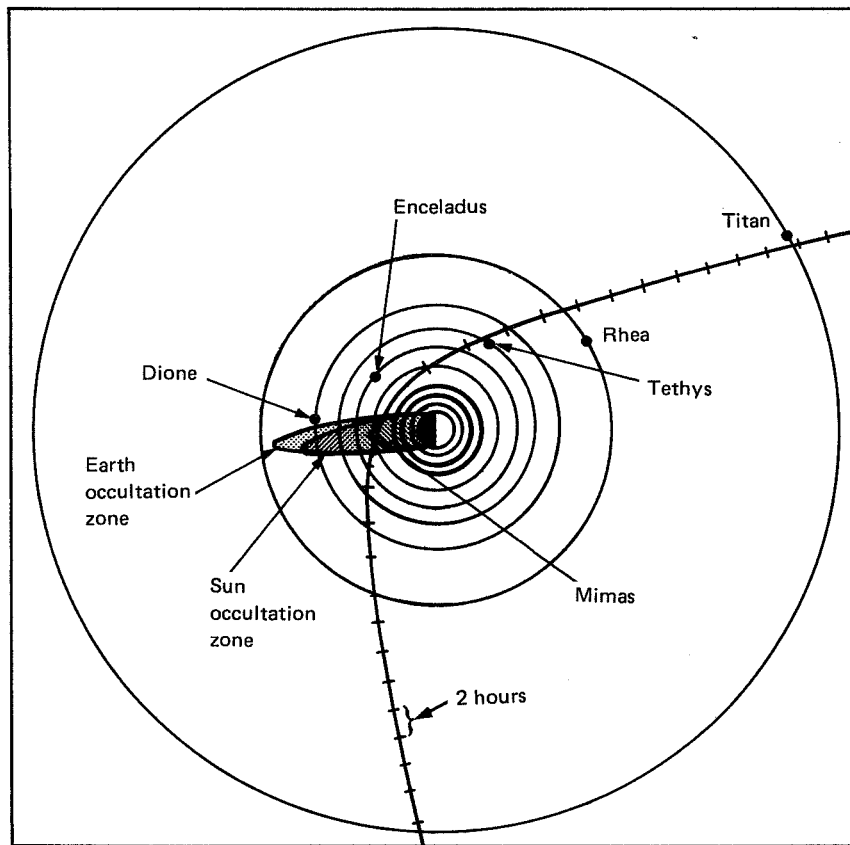
The second Voyager will reach Saturn in late August of 1981. The details of the encounter depend on a decision that will have to be made during the preceding winter or spring—whether to go for a Uranus encounter or not. Uranus and its system of five satellites (and recently discovered ring system) offer an extremely tempting target. The opportunity to explore that whole new world will not come again for another decade. In fact, it is only at 42-year intervals that the planet offers the fascinating sight of a polar axis pointed at the Sun.

The main consideration in the decision is whether the first Voyager encounter with Saturn has accomplished its objectives—most particularly those concerned with Titan and the rings. The condition of the second spacecraft is another important consideration. Will it be capable of performing the necessary maneuvers and activities for an exploration of Uranus in January 1986, more than eight years after leaving Earth?

If the decision is made to use Saturn's gravity field as a means of reaching Uranus, the Saturn encounter will take place August 27, 1981, at a distance of 2.7 Saturn radii. The path is only about 38 000 km beyond the visible edge of the outermost ring. The geometry of the encounter is shown in figure 6.

The Voyager, entering at the upper right of the drawing, will cross high above Titan's orbit about a day before periapsis. The flyby distance of about 350 000 km will not permit another thorough exploration of Titan. Five other satellites will be examined at closer range: Rhea, Tethys, Enceladus, Mimas (at only 34 000 km), and Dione. The planet will again occult the Earth, providing an opportunity to supplement the previous encounter's occultation observations. When the Voyager leaves the vicinity of Saturn, it will be very nearly in the ecliptic plane.

A decision not to go to Uranus would be implemented early in the summer of 1981 by a trajectory correction maneuver. The encounter would be essentially like the other Voyager's trip through the Saturnian system. The geometrical conditions at Saturn and Titan would be just about the same. Rhea would be seen at a greater distance, but the other four satellites would be closer.



Launch date: August 20, 1977

Saturn arrival date: August 27, 1981

<i>Satellite</i>	<i>Flyby distance (km)</i>
Titan	353 000
Rhea	253 000
Tethys	159 000
Enceladus	93 000
Mimas	34 000
Dione	196 000

Figure 6.—Voyager 2 encounter at 2.7 Saturn radii.

With either choice, the second Voyager will have completed its Saturn observations by the end of September. In their first four years of exploration, the Voyagers will have performed four detailed investigations of two planets and their systems. One of the

safest predictions is that our conception of the outer solar system will be substantially altered.

Out There

If the slower of the two Voyagers is indeed headed for Uranus (at 19 AU from the Sun), it will reach that planet in 1986. At that time, the Sun will be nearly over the north pole of Uranus, and the entire southern hemisphere will be in the middle of its years-long night. The equatorial plane, which seems now to include a ring system as well as the satellites, will be broadside to the Sun. The path of the spacecraft will be nearly perpendicular to the equatorial plane, and should permit the exploration of several satellites in addition to the planet itself.

The solar system as a whole is moving through galactic space. After all their planetary encounters both Voyager spacecraft will continue to recede from the Sun in the general direction of that motion. At some time they will cross the heliopause—the boundary between the Sun's magnetic and plasma domain and the general stellar wind. Since the location of the heliopause is unknown, the Voyagers may carry out that valedictory flourish of observations before communication at last ceases.

The Voyager Spacecraft and Its Investigations

The Mission Module

WE have been accustomed to thinking of planetary missions in terms of a launch vehicle and a spacecraft. The launch vehicle supplies sufficient velocity to the spacecraft to enable it to coast over a long time period to its encounter with the distant planet. The launch vehicle usually consists of several stages, and the spacecraft is carried by the final stage within a nose fairing that protects it on its passage through the Earth's atmosphere. Once the spacecraft has been injected into a coasting trajectory, it can make minor course corrections by burning propellant in its velocity-control rocket engine. It does not generally make large changes in its velocity en route, although if it is to orbit a planet it must decrease its velocity by a substantial amount when it arrives in the planet's vicinity.

With this outer planets mission, however, the old distinction between launch vehicle and spacecraft becomes blurred. The launch vehicle, which consists of a Titan IIIE first stage and a Centaur D-IT upper stage, is not capable by itself of imparting enough energy to inject a Voyager spacecraft into a Jupiter trajectory. The final increment of launch velocity is provided by a solid-propellant rocket that constitutes the Propulsion Module of the spacecraft. The part of the spacecraft that makes the entire journey (i.e., the Voyager) is the Mission Module. This arrangement provides advantages in performance and reliability through the use of the Mission Module's guidance and control electronics and propellant to stabilize the composite spacecraft's attitude during the one-time operation of the Propulsion Module. The Propulsion Module is shown as part of the spacecraft in figure 7.

The total mass of the composite spacecraft is 2016 kg. Shortly after the burnout of the solid rocket, the Propulsion Module is jettisoned, and the 792-kg Voyager is on its way to Jupiter. (During the remainder of this description, "spacecraft" and "Voyager" will

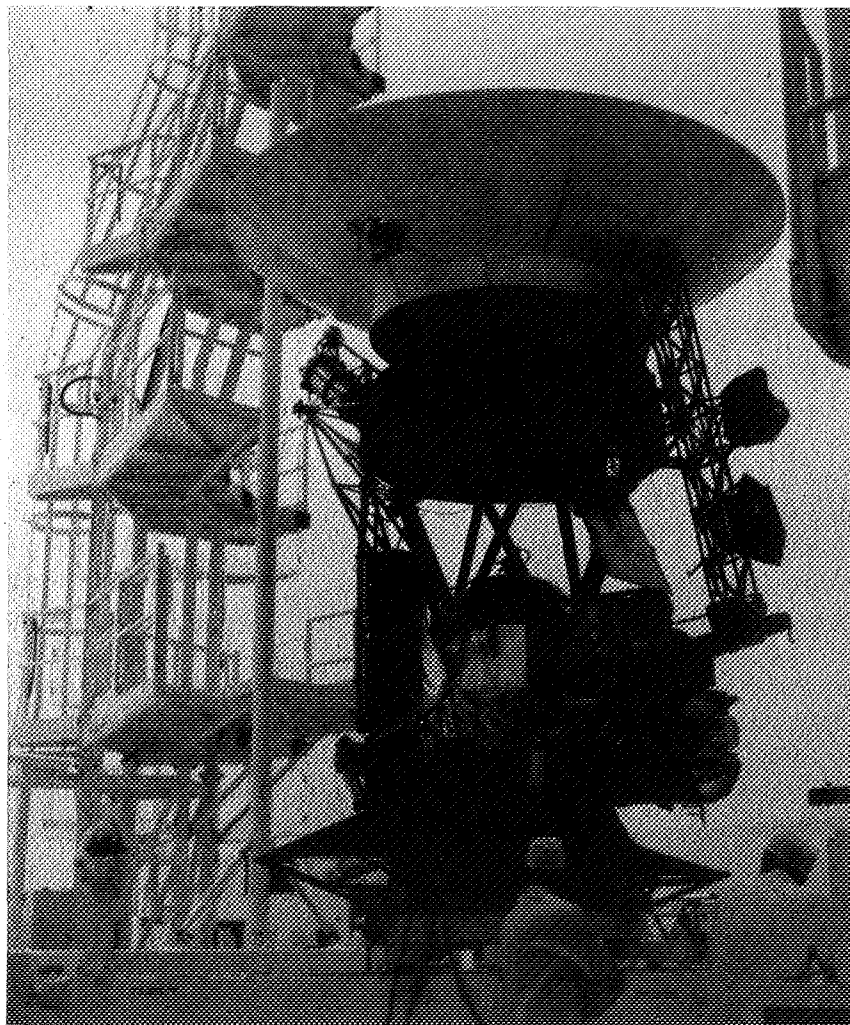


Figure 7.—Voyager spacecraft consisting of Mission Module and Propulsion Module shown in launch configuration with stowed appendages.

be used to designate the Mission Module that makes the journey to the outer planets.)

Although the basic design of the Voyager spacecraft is derived from the earlier Mariner spacecraft and the Viking Orbiters that are now circling Mars, the family resemblance is effectively hidden by Voyager's conspicuous appendages (fig. 8). Particularly evident is the very large (3.7 m) parabolic antenna that is located about where the solar panels were attached to the predecessor spacecraft. This

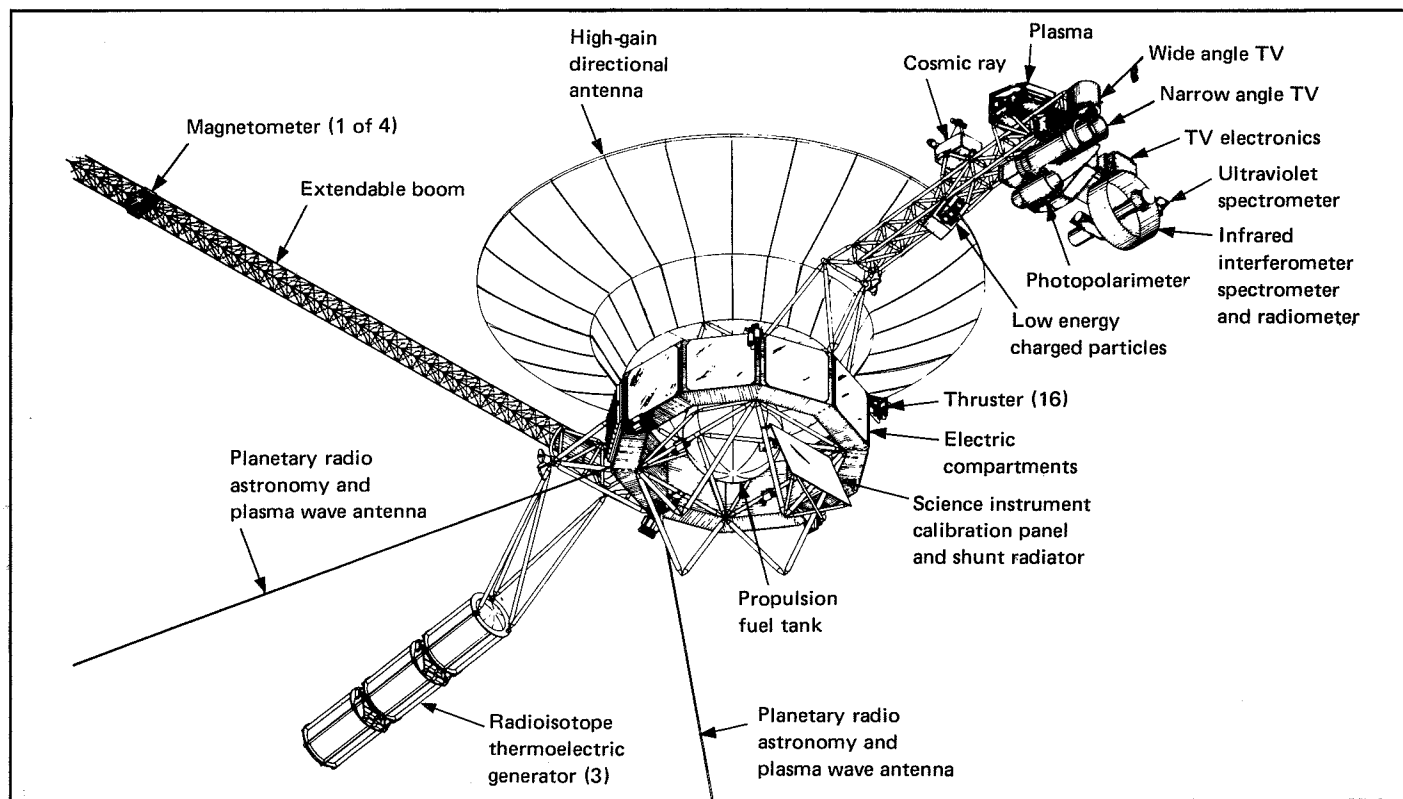


Figure 8.—Schematic diagram of deployed Voyager.

substitution is a striking reminder of the vast distances separating the outer planets from both the Sun and Earth.

Solar panels were discarded as the electrical power source because the solar illumination is so ineffective at the distances where the spacecraft will operate. At Saturn's distance of 10 AU, the solar panel area required for a given power output would be 100 times that which is needed in Earth orbit. Therefore, radioisotope thermoelectric generators (RTGs) are used to supply electrical power to the spacecraft. Three of these generators are mounted on a boom to help isolate the main subsystems from excess heat and radioactivity. The energy source for each RTG is heat from the radioactive decay of plutonium oxide. The generator consists of a bank of thermoelectric elements that convert the temperature difference between their ends into electrical power. The combined thermal output will be about 7000 W by the time Voyager reaches Saturn, and it will be converted to 390 W of electrical power.

The Voyager's radio transmitters use a high-gain antenna to concentrate the radiated energy into a beam and to maintain a reasonable signal strength even at very great distances. The antenna is a parabolic reflector of very large aperture, when compared with the other spacecraft components. The antenna's beam pattern is further sharpened by the use of X-band transmission in place of the S-band frequency employed by the Mariners. The antenna's beamwidth with X-band transmission is a fourth of its S-band beamwidth. The spacecraft transmits only in the S-band during the cruise phases of the mission, when a high data rate is not required.

The data rate during cruise depends on the distance, declining from 2560 bits (binary digits) per second (bps) near the Earth to 80 bits beyond Saturn. When periodic science maneuvers are performed during the cruise, the rate is increased to 7200 bps. This is also the rate allocated to engineering telemetry and science data (exclusive of the imaging science investigation) during the Jupiter and Saturn encounters. Imaging science data will use all the remaining available transmission capacity during the encounters. The total data rate at Jupiter can be as high as 115 200 bps, and at Saturn 44 800 bps. Such high data rates at those distances are particularly impressive when we recall that only a dozen years ago Mariner 4 transmitted the first pictures from the vicinity of Mars at the agonizingly slow rate of 8-1/3 bps.

The axis of the parabolic reflector is also the roll axis of the spacecraft. It is kept pointing directly at the Earth throughout the

mission, except during velocity-control and science maneuvers. Although the roll axis is not aimed at the Sun, as it was on other Mariners, the Sun is still the primary attitude reference. From the distance of the outer planets, Earth and the Sun are never far apart. (At Saturn's distance, the maximum separation is 6° .) The spacecraft Sun sensor views the Sun through a hole cut in the reflector. Another sensor, mounted approximately perpendicular to the axis, locates the star Canopus to provide a roll attitude reference. During maneuvers, and when celestial reference signals are not available, an inertial reference unit maintains the orientation references.

The spacecraft's main body is a polygonal 10-sided ring that houses the electronic equipment. It provides some protection from micrometeoroids and radiation, and it maintains a suitable thermal environment by means of louvers that adjust the area available for thermal radiation.

Distributed around the periphery of the ring are the 16 thrusters that maintain the spacecraft attitude and produce the velocity changes required for trajectory corrections. On this spacecraft, unlike previous Mariners, one subsystem performs both functions. All the thrusters generate their thrust by the decomposition of the monopropellant hydrazine. Four of the thrusters point in the same direction, and are operated simultaneously for velocity changes. The remaining thrusters produce torque couples about the roll, pitch, and yaw axes to control attitude. The hydrazine tankage and tubing that supply the spacecraft thrusters also supply the larger thrusters that stabilize the Propulsion Module during the burn of its solid-propellant rocket. About one-twentieth of the hydrazine supply is expended for that purpose. All the thrusters are under the control of the same electronics.

During the encounter phases of the mission, while the spacecraft maintains an orientation that points the parabolic antenna directly toward Earth, one set of sensors must be accurately aimed at a long succession of objects of scientific interest. In order to accomplish this, the sensors for the imaging science, infrared radiation, polarimetry, and ultraviolet spectroscopy investigations are mounted on a Science Scan Platform (fig. 9) that can be precisely rotated about two axes. The sensors are boresighted to point in a common direction.

The boom that supports the Science Scan Platform provides a convenient place to mount the particle sensors for the cosmic ray, low energy charged particle, and plasma particle investigations.

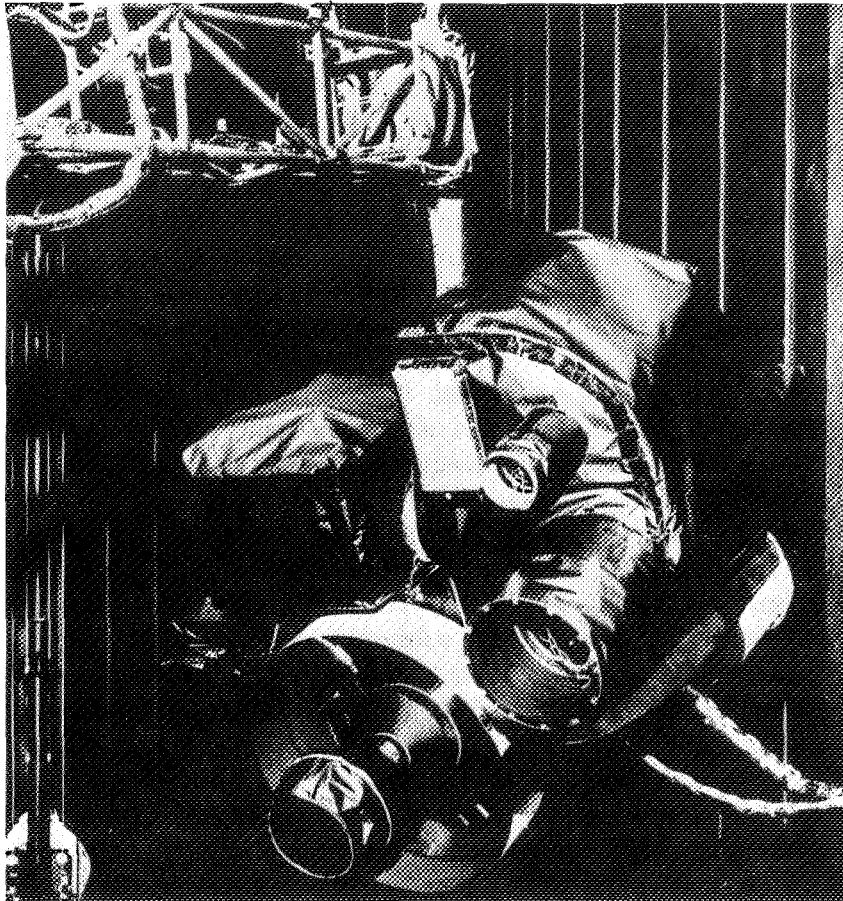


Figure 9.—Science Scan Platform instruments.

These sensors all require fixed orientations with respect to the spacecraft, along with wide unobstructed fields of view.

The third very conspicuous boom attached to the Voyager spacecraft supports the sensors for the magnetic fields investigation. The quality of the data from the low-field magnetometers depends on their remoteness from the spacecraft's own magnetic field. They are therefore carried at the end of a 13-m-long deployable boom.

This remarkable boom, together with its two low-field magnetometers, is stowed like a jack-in-the-box inside a canister that is only 23 cm in diameter and 66 cm long. It is a triangular truss whose fiberglass longitudinal members are held in place by fiber-

glass triangles that are spaced 14 cm apart. The truss is stiffened with tensioned, collapsible diagonal filaments.

The boom is stowed by twisting the entire structure so that the diagonal filaments interlace and the triangles are nearly in contact with each other. This puts a considerable elastic force on the assembly. When the canister is opened by a pyrotechnical device, a lanyard that is paid out at a controlled speed prevents the boom from popping out with destructive violence.

The two remaining appendages are the long, thin, deployable antennas that are used jointly by the planetary radio astronomy and the plasma wave investigations.

To assure proper operation for the four-year flight to Saturn, and perhaps well beyond, all of the spacecraft's subsystems have been designed for high reliability. Much reliance is also placed on functional flexibility and extensive redundancy of key components. Three of the subsystems use reprogrammable digital computers to maintain their flexibility of response to changing conditions and requirements during the long mission. These are the command control subsystem (CCS), the attitude and articulation control subsystem (AACS), and the flight data subsystem (FDS). Each has two computers for redundancy.

The CCS is the heart of the on-board control system. It issues commands to other spacecraft subsystems from its memory. It can decode commands from the ground to update its memory, and can pass the commands along to the other subsystems. The CCS can survive any single internal fault, because each of its functional units has a duplicate elsewhere in the subsystem.

The AACS controls the propulsion subsystem, maintains the spacecraft's attitude, and positions the Science Scan Platform. It has two plated-wire memories and redundant processors for them.

The FDS controls the scientific instruments and arranges all the science and engineering data for telemetering to Earth. It has two data processors and two memories that provide both flexibility and redundancy.

In addition to its own memory units, the FDS controls the data storage subsystem, which is a high-capacity digital tape recorder. The 8-track tape can record about 536 million bits (the equivalent of 100 image frames), and can play the data back at four different speeds.

Redundancy is also greatly in evidence in the communications components. There are two receivers, two traveling-wave-tube

(TWT) amplifiers for X-band transmission, and both a TWT and a solid-state amplifier for S-band transmission.

Imaging Science Investigation

Visual images have been the most valuable source of remote-sensing information in deciphering the stratigraphy and structure of the solid planetary bodies that have been examined, and they provide the means of relating the data acquired by other remote sensors to particular features of a planet's surface. Because of the differing characteristics of the various planetary bodies, imaging science plays a variety of roles in their exploration. The Galilean satellites of Jupiter, with their optically thin or nonexistent atmospheres, should be amenable to the same kinds of image analysis as the inner planets. The surface of Saturn's largest satellite, Titan, may be obscured by its atmosphere in the manner of Venus. As for the giant planets themselves, Jupiter and Saturn do not have solid surfaces, and imaging science is principally concerned with the tops of their cloud layers.

One set of specific objectives for the imaging science investigation is concerned with the motions of the cloud systems of Jupiter and Saturn and what they may reveal about the global atmospheric circulations. Sequences of images over an extended time period will observe the motions in the boundary regions between the belts and zones, and the motions in the neighborhood of such large atmospheric features as the Great Red Spot.

Other objectives are to characterize the colored materials in the cloud belts and zones and to determine the vertical structures of the clouds and the high-altitude scattering layers. For the latter purpose, the Voyager will photograph the planets' limb and terminator regions during the close encounters.

The mission will make comparative geological studies of the satellites possible by photographing about ten of them at resolutions finer than 15 kilometers. Imaging science will determine the size and shape of many of the smaller satellites, and establish coordinate systems for the larger ones.

Several objectives apply to Saturn's rings. Their optical scattering properties will be investigated by photometric imagery over a wide range of phase angles, and at several wavelengths. The imaging science experiment will investigate the radial distribution of the ring particles by imaging large portions of the rings at moderate

resolution from positions well above or below the plane of the rings.

The subsystem that will perform the imaging science observations consists of a pair of television cameras mounted on the Science Scan Platform. Television systems employing slow-scan vidicon cameras have provided the visual imagery on planetary missions from Mariner 4 onward. The image on the target plate of these cameras is erased each time a picture has been scanned out, thus making the camera available for further photography at once, and over a period of years. Photographing a complete feature of interest at high resolution usually involves assembling a mosaic of a number of pictures.

The pictures of Jupiter obtained on the Pioneer 10 and 11 missions were from the imaging photopolarimeter experiment, which was neither a film camera nor a television camera. The imaging photopolarimeter made ingenious use of the spin-stabilized Pioneer spacecraft to scan its light-sensitive field across the planet's face and build up a coarse two-dimensional image. The fully stabilized attitude of the Voyager spacecraft permits the use of television cameras to photograph very much finer details at very much shorter time intervals.

Each camera of the imaging science subsystem (fig. 10) comprises a lens, filter wheel, shutter, and slow-scan vidicon tube with associated electronics. The lens for the wide-angle camera has a focal length of 200 mm, and a relative aperture of $f/3.5$. The narrow-angle camera uses a catadioptric telescope (one that combines reflecting and transmitting elements) with a focal length of 1500 mm and a relative aperture of $f/8.5$. The field of view of the wide-angle camera is 56 by 56 mrad, so that at a range of 1000 km one picture would cover a square 56 km on a side. The field of view of the narrow-angle camera is only 7.4 by 7.4 mrad. The optic axes of the two lenses are boresighted to point in precisely the same direction, so that simultaneous imaging provides nested coverage.

An eight-position filter wheel on each camera permits the selection of a wide range of spectral transmittances and thereby allows the reconstruction of color images. The two filter wheels are independently controlled, and their positions can be changed from picture to picture by commands stored in the memory of the flight data subsystem.

Slow-scan cameras, unlike those used for broadcast television, employ shutters to control the duration of an exposure. Exposure

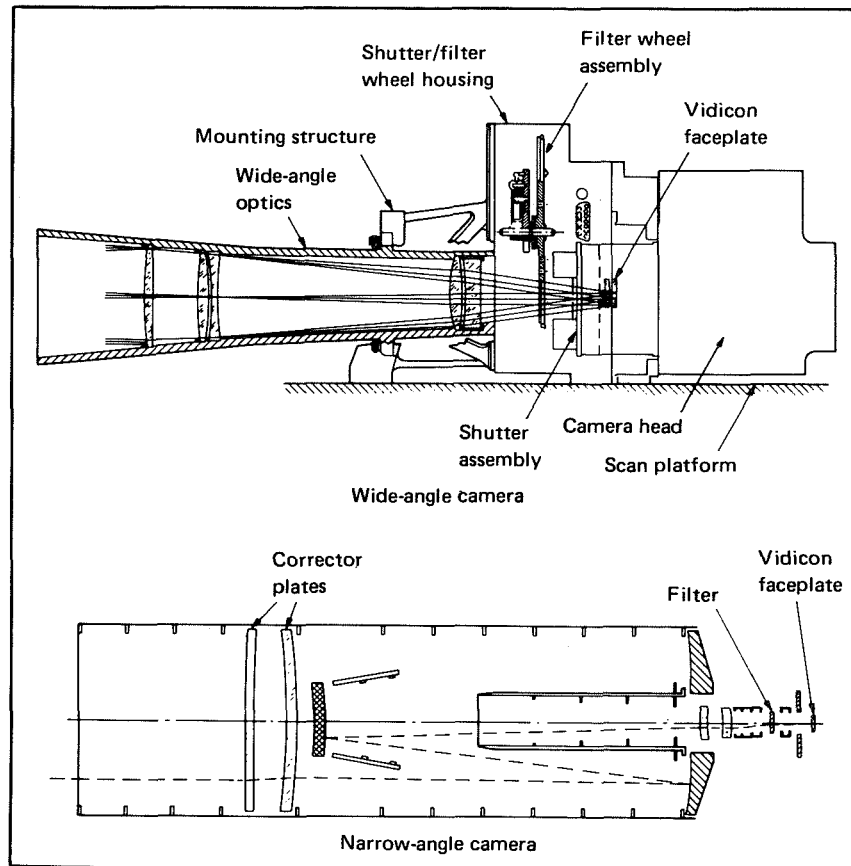


Figure 10.—Imaging science instruments.

times between 0.005 and 15 sec can be selected in the fixed mode, and much longer exposures in the long-exposure mode.

The sensing element of each camera is a vidicon tube. The image formed by the lens is exposed by the shutter onto the vidicon's target plate, which bears a layer of photoconductive material. A two-dimensional image in the form of electrostatic charges is recorded on the plate. A scanning beam of electrons reads out the image line by line, converting it into a sequence of electrical signals. In the normal readout mode it takes 48 sec to scan the 800 lines of a single image. Slower scanning rates are also selectable. Each line is composed of 800 picture elements (pixels). The electrical signal arising from each pixel is assigned one of 256 discrete intensity

levels. Since 256 equals 2^8 , it takes eight binary digits (bits) to distinguish that many levels, and each pixel is treated by the flight data system as an 8-bit digital word.

Images can either be transmitted to Earth in real time (as they are read out by the scanning beam), or recorded in digital form on tape for later transmission. The normal readout mode is compatible with the 115 200 bit-per-second transmission rate at Jupiter's distance. The tape recorder accepts imaging data at the same rate. It has storage capacity for about 100 frames. To transmit images from Saturn in real time at 44 800 bps, the scanning time is increased to 144 seconds per frame. These images include the full frame, at full resolution. There are also editing modes available, in which not all the pixels composing the frame are transmitted.

The encounters with the various planets and satellites during this mission will occur at widely varying distances. A knowledge of the nominal angular resolution of each camera makes it possible to predict the sizes of detail that could be distinguished on the images. Since a pair of scan lines in the narrow-angle camera covers a field angle of $19 \mu\text{rad}$, the camera could theoretically resolve about 19 m at a distance of 1000 km. Table 2 shows the predicted resolutions for the narrow-angle cameras at the currently planned closest

Table 2.—*Imaging Resolution of Satellites*

Satellites	Resolution, km	Coverage, %
Jovian:		
Io	0.5 to 2	50
Europa	4 to 6	40
Ganymede	1 to 3	40
Callisto	3 to 4	35
Amalthea	8 to 10	35
Saturnian:		
Mimas	2 to 3	30
Tethys	4 to 6	30
Enceladus	6 to 8	30
Rhea	2 to 4	30
Dione	2 to 4	30
Iapetus	20 to 25	15
Hyperion	10 to 12	15
Titan	2 to 4	50

approach distances to the various planetary bodies. Resolved detail in the wide-angle images will be coarser by a factor of about 7-1/2.

Infrared Radiation Investigation

Infrared radiation comes to the Voyager spacecraft from the planets and their satellites both by thermal emission and by the reflection of solar radiation. The temperatures of the emitting surfaces or atmospheric layers are so low that nearly all of the thermal radiation is in the far infrared, whereas solar radiation is more intense at near infrared and visible wavelengths.

Atmospheric gases have various absorption bands throughout the infrared, and the reflected solar radiation shows reduced intensities at some of those wavelengths. The effectiveness of particular absorption bands depends on the chemical composition and on pressure and temperature conditions. It is through these effects that the infrared radiation investigation will acquire information on the composition and thermal structure of planetary atmospheres (including that of Titan) to complement that provided by the ultraviolet spectroscopy investigation.

Infrared radiation from satellites with tenuous atmospheres contains information about surface composition, temperature, and thermal and optical properties, as well as atmospheric composition information. The investigation will also obtain spectra from Saturn's rings, permitting studies of their composition and radial structure, and of the size and thermal properties of the ring particles.

The investigation includes a radiometer that measures the total reflected radiation in the visible wavelengths and a portion of the near infrared wavelengths. In combination with the reflection and thermal emission information derived from the infrared spectra, this permits studies of the energy balances of the planets and their satellites.

A prime objective is the investigation of the heat balances of the outer planets. Jupiter is known to radiate about twice as much heat as it receives from the Sun. Recent telescope measurements indicate that Uranus also radiates more heat than it receives, while at present the evidence on Saturn's overall heat balance is conflicting. The existence of an internal heat source such as Jupiter's bears on questions concerning the origin and evolution of the planets as well as the dynamics of deep atmospheres that are transporting heat outward.

Studies of atmospheric dynamics require knowledge of local energy balances. The zones and belts that are so clearly visible in the atmospheres of Jupiter and Saturn are doubtless associated with latitudinal variations in heat flow as well as with the very rapid rotations of both planets. If Saturn's overall balance of internal and solar heat turns out to be markedly different from that of Jupiter, local energy balance determinations may explain the similarities in the two planets' zone and belt structures.

The atmosphere of Uranus must reflect, in its regional heat balance variations, the fact that the planet's polar axis is nearly in the orbital plane. Titan's atmospheric behavior should be different from those of the rapidly rotating planets if the presumed synchronization of its rotation with its orbital period is correct.

A second major objective is the study of the atmospheric compositions of the planets and their satellites. The mixing ratios of the main gaseous constituents and the concentrations of the less common gases can be derived from the infrared and ultraviolet spectrometric investigations. The ratio of molecular hydrogen to helium is of particular importance to theories of the early formation of the solar system. Some theories assume that Jupiter, Saturn, and Uranus are representative of the primordial solar nebula. If the relative abundances of the light elements are nearly the same for the three planets, the case for that assumption will be quite strong.

The relative abundances of the isotopes of the light elements are important to cosmogonic theories for similar reasons. The ratio of deuterium (H^2) to hydrogen, and that of C^{12} to C^{13} are of greatest interest. Because methane (CH_4) has so many absorption bands in the infrared, it should be possible to infer the isotopic ratios of both elements from the infrared data.

The investigation of clouds and hazes (aerosols) in the atmospheres of the planets and Titan is another objective. Their chemical compositions can be determined from the positions of absorption features in the reflected solar infrared spectra. Clouds and hazes can be differentiated in the emission portion of the spectrum. It is also possible to infer the heights of cloud tops and the particle size and relative opacity of hazes. The study of Titan's clouds is of particular biochemical interest because it is the only satellite in the solar system known to have a cloudy atmosphere and it may have conditions favorable to the formation of complex organic molecules.

The surfaces of most of the satellites (Io is an exception) are at

least partially covered with ice. The ices of water, ammonia, and methane are readily distinguished in spectra of the near infrared. Although minerals have more subtle spectral characteristics than ices, certain groups of silicate minerals can be distinguished. Some non-silicate minerals of interest, such as the sulfates that are believed to be present on Io, are readily detectable. The spatial resolution of these measurements will permit surface composition mapping of the Galilean satellites, and globally averaged determinations for some of the others.

The objectives with respect to Saturn's rings include the investigation of the composition and size of the ring particles and their distribution within the rings. While the two bright rings are known to contain water ice, the composition of the faint rings remains to be determined. The instrument can determine particle size over a wide range, from a radius of a few micrometers to a few centimeters.

There are currently two versions of the infrared instrument. The improved instrument is designed for the very distant Uranus encounter. If it is not completed and qualified in time for the mission,

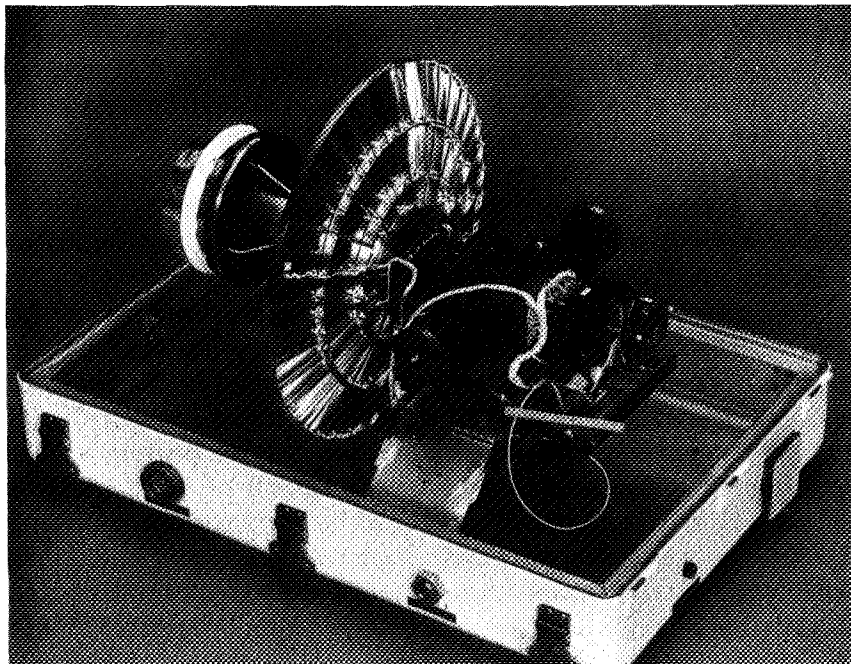


Figure 11.—Infrared interferometer spectrometer.

the earlier version, which was only designed for the Jupiter and Saturn encounters, will be carried.

The new instrument (fig. 11) consists of a telescope for collecting the infrared radiation, two interferometers for acquiring spectral data in the near and far infrared, and a radiometer for measuring the total reflection over a band of wavelengths.

The early instrument with a single Michelson interferometer has a spectral wavelength range of 2.5 to 50 μm , a field of view of 0.25° , and a system operating temperature of 200 K. The new instrument has two Michelson interferometers to extend the spectral range, and it operates at a lower temperature to give greater sensitivity. It has a spectral wavelength range of 1.4 to 10 μm and 15 to 200 μm , a field of view of 0.15° , and a system operating temperature of 140 K. The two versions of the instrument are interchangeable on the spacecraft.

Photopolarimetry Investigation

Non-luminous objects become visible by scattering incident light. Whereas the imaging science investigation has the function of resolving the scattered light to produce images, the function of the photopolarimetry investigation is to provide information about the properties of light-scattering surfaces or atmospheric particles. It does this by measuring the intensity of scattered light at selected wavelengths and polarization angles.

The light that the Sun radiates over a broad band of wavelengths is unpolarized. That is to say that the light waves vibrate equally in all of the infinite number of planes that are perpendicular to the direction of propagation. When this light is scattered by particles in an atmosphere or on a surface, the scattered light is polarized to some extent; i.e., the intensity of the light vibrating in some planes is higher than in others. With light that is completely plane-polarized (by means other than scattering), the intensity is zero in the plane perpendicular to the plane of maximum intensity. By measuring light intensities separately through three plane-polarizing filters oriented 60° apart, a photopolarimeter can determine both the degree and the plane of polarization.

The Voyager instrument makes its measurements in eight discrete wavelength bands, ranging from 2350 Å in the ultraviolet portion of the spectrum, through the visible, to 7500 Å in the near infrared. It measures at 5 positions of the polarization analyzer wheel, so that a single observation comprises 40 measurements.

To know the complete light-scattering behavior of a given target, it is generally necessary to repeat the observation under different geometrical conditions of illumination and viewing. The significant variables involve one or more of three angles: phase angle, illumination angle, and viewing angle. The phase angle is the angle made at the target by the Sun's direction and the instrument's direction (projected to the plane containing both directions). The illumination angle at a surface is the angle between the normal to that surface and the Sun's direction. The viewing angle is the angle between the surface normal and the instrument's direction.

Earthbound photopolarimetry of the outer planets is limited to a very small range in these angles. The phase angle is never more than 12° at Jupiter or 6° at Saturn. During Voyager encounters, these planets and their satellites will be viewed at phase angles up to 160° .

The main purpose of the photopolarimetry investigation is to determine the physical and chemical properties of particulate matter in the atmospheres of the planets, Titan, and other satellites that may have thin atmospheres; and the surfaces of satellites that have little or no atmospheres. The rings of Saturn, which may be aggregations of very small satellites, may also contain small amounts of particulate matter.

A major set of objectives concerns the various kinds of clouds in the atmospheres of Jupiter, Saturn, and Titan. One is to define the overall structures of the clouds by determining the vertical distribution of their particles. A related objective is to study the nature of the individual cloud particles in various regions: their size, shape, and probable composition.

A second set of objectives is concerned with the surfaces of those satellites that do not have light-scattering atmospheres. The variation of the polarization with phase angle provides information on the physical characteristics of the material at the surface. It will be possible to distinguish among bare rock surfaces, dust, frost deposits, ice, and regoliths produced by repeated impacts.

Learning the surface composition of as many satellites as possible is an important Voyager objective. The photopolarimeter's capability for obtaining accurate spectral photometry can provide some data on surface composition for all the satellites of Saturn and at least seven of the Jovian satellites.

The objectives with regard to the rings of Saturn are to provide information on the size distribution and shape of the ring particles,

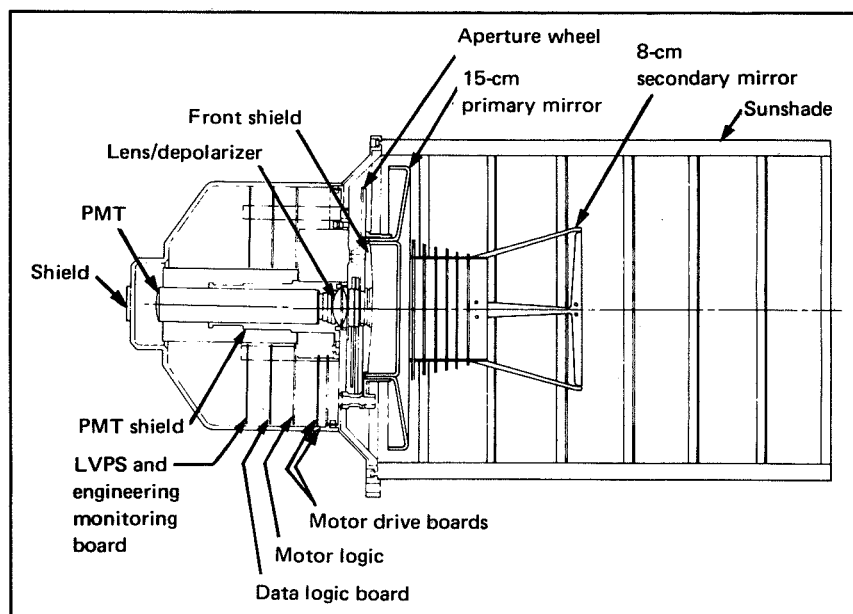


Figure 12.—Photopolarimeter configuration.

their composition, and their density and radial distribution. The photopolarimeter will acquire its data in two modes: scattered sunlight measurements, and observations through the shadowed portion of the rings of the extinction and scattering of the light from bright stars.

The Voyager photopolarimeter, designed primarily for the encounter phase of the mission, is mounted on the spacecraft's Science Scan Platform, with its line of sight boresighted to the imaging science system's narrow-angle camera. The instrument (fig. 12) consists of a telescope, a photomultiplier tube, three motor-driven wheels that select the field of view and the wavelength band and polarization plane of observation, and associated electronics.

Ultraviolet Spectroscopy Investigation

The outer planets, because of their strong gravitational attractions and low temperatures, retain even the lightest gases in their atmospheres. Thus, the atmospheres are probably close approximations of the original composition of the primordial solar nebula at their respective heliocentric distances.

Atmospheric gases emit radiation at certain of the far ultraviolet wavelengths as a result of either the resonance scattering of solar ultraviolet radiation or excitation by bombardment with energetic particles. This airglow can be analyzed by a sufficiently sensitive spectrometer. When sunlight passes through the atmosphere, resonance scattering causes a reduction in the transmitted energy at those wavelengths. Most of the gases with which this investigation is concerned also have continuous absorption bands below some characteristic wavelength. A spectrometer aboard a spacecraft that is entering or leaving a planet's shadow can analyze this atmospheric extinction spectrum by looking at the Sun. The Voyager ultraviolet spectrometer will operate in both the airglow and solar occultation modes during encounters with Jupiter, Saturn, Uranus, and some of their satellites.

The ultraviolet wavelength band of the electromagnetic radiation spectrum extends from about 50 Å to 4000 Å. The Voyager ultraviolet spectrometer analyzes the portion of the ultraviolet band between 500 and 1700 Å. This portion is the far ultraviolet.

The primary objective of the ultraviolet spectroscopy investigation is to determine the concentration of the main constituents and the structure of the atmospheres of Jupiter, Saturn, Titan, and, possibly, Uranus. The atmospheres are believed to consist mainly of atomic hydrogen, molecular hydrogen, helium, and methane.

Another objective is to study the atmospheres of the Galilean satellites and to search for toroidal (ring-shaped) clouds of gas along their orbits. Io's orbit has at least two such clouds: a sodium cloud extending all around the orbit detected by Earth-based spectroscopy, and a cloud of hydrogen detected by Pioneer 10's ultraviolet photometer.

The existence of far-ultraviolet spectrometers sensitive enough to meet the foregoing objectives aboard two long-lived spacecraft provides an unexcelled opportunity for some exploratory astronomical observations. Long observation times in the airglow mode during the cruise phases of the missions will permit pursuit of several additional objectives.

One astronomical objective is to perform a comprehensive survey of the stellar sources of extreme ultraviolet radiation that have been identified recently by rocket-borne spectrometers. There will be about 8 hours of observation time for each source that was briefly glimpsed from rocket flights.

The ultraviolet spectrometer (fig. 13) is an instrument that must function in two distinctly different modes. In the airglow mode, it must be as sensitive as possible to the weak far-ultraviolet emissions that it observes. In the occultation mode, it must look directly at the Sun and accurately measure rapidly changing atmospheric absorption. The instrument is mounted on the spacecraft's Science Scan Platform, with its airglow-observation field of view bore-sighted to that of the imaging science subsystem's narrow-angle camera. A mirror offsets the occultation-observation field of view by 20° , so that the other instruments on the Science Scan Platform are not damaged by the Sun.

Figure 14 is a simplified optical diagram of the ultraviolet spectrometer. The field of view, which is fixed by the slits in a series of 13 opaque plates, is about 0.1° (in the plane of the diagram) by 0.9° . The incident radiation is dispersed into a spectrum by the diffraction grating at the back of the spectrometer. Only reflective

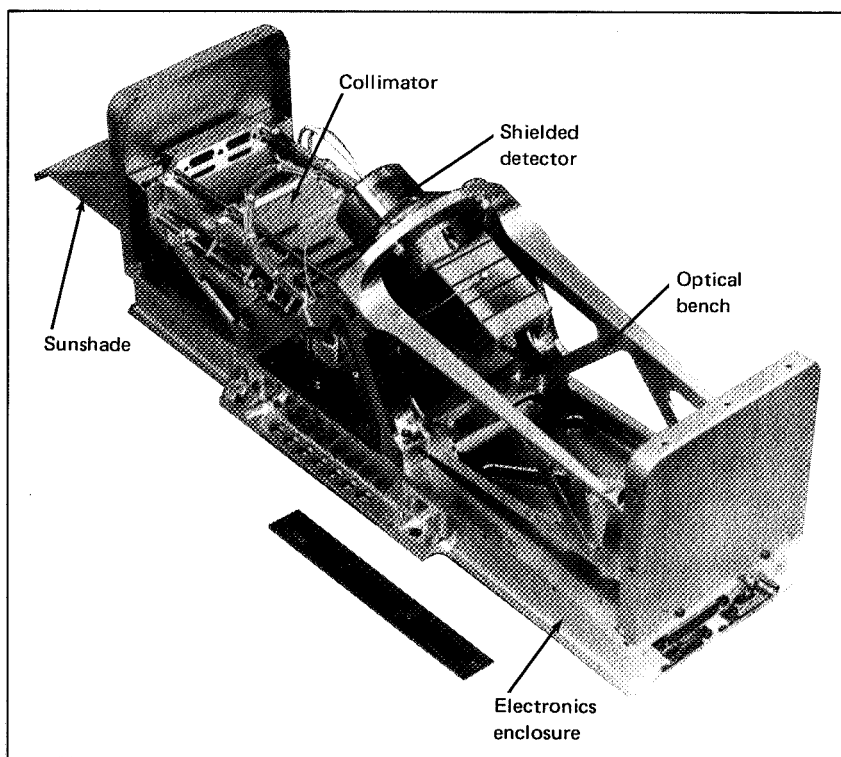


Figure 13.—Ultraviolet spectrometer.

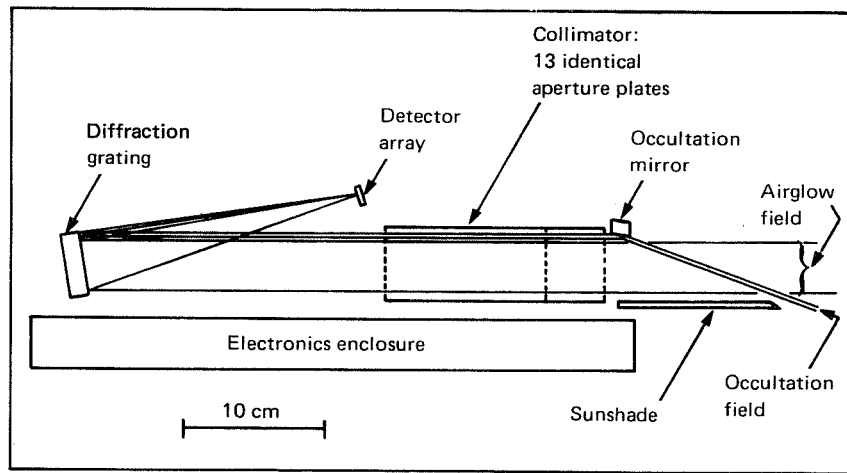


Figure 14.—Schematic diagram of ultraviolet spectrometer.

optics can be used in the far ultraviolet, because no solid transmits wavelengths shorter than $1050 \text{ \AA}$. The spectrum produced by the diffraction grating is imaged on the detector array.

Radio Science Investigation

The success of these outer planet missions requires new levels of communications and tracking performance. Although the radio equipment is not especially dedicated to this investigation, some requirements have been upgraded to improve capabilities for radio science. Also, the spacecraft trajectories have been designed to provide radio occultations by the planets, the rings of Saturn, and Titan.

As a planet is interposed between a spacecraft and Earth, the radio paths can traverse the planet's magnetosphere, ionosphere, and atmosphere in turn. Each region affects the radio signal characteristics in its own way, so that it is possible to study its structures and disturbances from occultation data.

Throughout the missions, the radio paths will be traversing the interplanetary medium. With two spacecraft in the same part of the sky at different distances, the radio signals will permit a study of the flow patterns of solar wind disturbances. When the paths lie near the Sun, the effects of the solar corona and the relativistic signal delay caused by the solar gravity field will be observed.

One set of objectives is to investigate the structure of the

atmospheres of Jupiter, Saturn, and Titan. This will be done by continuous measurement of the received frequencies and intensities of the radio signals from the spacecraft's S-band and X-band transmitters.

The atmospheric pressure of any planet's atmosphere increases as one descends toward the surface. That is the basis for the use of barometric altimeters in airplanes. The velocity of light (or radio) wave propagation, which is constant in a vacuum, decreases with increasing atmospheric pressure. To put it another way, the atmosphere's index of refraction increases with pressure. Rays passing through an atmosphere are refracted from a straight-line path by the variation in pressure. When a spacecraft is entering occultation the rays are increasingly refracted, and the lengthening optical path produces a Doppler shift in the received radio frequencies. Refractive dispersion also reduces the intensity of the received signals as the angle of refraction increases. By cross-checking the frequency and intensity measurements, it is possible to derive a profile of the atmosphere's refractivity. Then, with a knowledge of the atmosphere's composition and its temperature at some altitude (from data supplied by the mission's ultraviolet and infrared investigations), the refractivity profile can be converted to temperature and pressure profiles.

Radio signal intensity can also be diminished during the occultation experiment by cloud layers in the atmosphere. Since cloud absorption does not affect the Doppler frequency, it should be possible to distinguish cloud layers, and to determine their altitudes and densities.

Another objective is to study local and regional variations in the atmospheric profiles due to weather and turbulence. It should be possible to sort out fluctuations in the frequency and intensity measurements that are due to turbulence by their characteristic rates and amplitudes at the S-band and X-band wavelengths.

An important objective of the occultation investigations at Jupiter, Saturn, and Titan is the measurement of their ionospheres. This can provide information bearing on the composition, photochemistry, and dynamics of the upper atmosphere. The refractivity of an ionospheric layer depends on its concentration of free electrons. Refractivity profiles of the ionosphere are derived from the radio data in a generally similar manner to those of the neutral atmosphere, except that the dual transmission at two wavelengths becomes a more powerful tool. That is because the ionospheric

refractivity is a function of the square of the wavelength, whereas the refractivity of neutral atmospheres is essentially independent of wavelength. Another difference is that ionospheric layers can refract both upward and downward, producing ray crossings.

A significant source of help in separating the ionospheric occultation data from the effects of the interplanetary medium and the Earth's ionosphere is the presence of a second transmitting spacecraft in the same part of the sky as the spacecraft that is being occulted.

The first Voyager spacecraft to encounter Saturn will be occulted by the ring system immediately after it emerges from occultation by the planet. The objective of this very important occultation investigation is to study the character of the rings. It should be possible to infer the total amount of material in each major ring zone, its radial distribution, and something of the composition and size distribution of the particles.

During encounters with planets and satellites, tracking reveals the effects of their gravitational fields. A general objective is to measure the masses of the bodies encountered and, where possible, to measure the harmonic coefficients of their gravitational fields (that is, the fields' departures from a spherical shape). These results are needed for modeling their interiors.

Since the two spacecraft will fly by Jupiter at much greater distances than Pioneers 10 and 11 did, little improvement in the knowledge of that planet's gravitational field is expected. However, the missions will provide improved information on the masses and densities of the Galilean satellites, to help define their internal structures.

The two Saturn encounters will be close enough to the planet to permit measurement of the harmonics of its gravitational field. The effect of Saturn's rings on the encounter trajectories should be distinguishable from the planetary harmonics, and it appears possible to derive good values for the total mass of the rings, and the individual masses of the A and B rings. The very close approach to Titan will permit an accurate measurement of that satellite's mass and density and some determination of its gravitational harmonics.

Another objective will involve studies of the solar corona and the solar wind. Radio signals passing through the corona when the spacecraft is near solar conjunction will permit annual observations of coronal electron density. Radio measurements will provide a continuous monitoring of the solar wind electron density between

the spacecraft and Earth. This should permit the study of the large-scale flow patterns of the solar wind and of the variations of solar wind density with distance from the Sun.

When the radio signals pass in the vicinity of the Sun at conjunction, they are delayed by the Sun's gravitational field—an effect predicted by the general theory of relativity. The Voyagers, with their annual solar conjunctions, will provide multiple opportunities to test the agreement between the predicted and the observed effects.

Cosmic Ray Particles Investigation

Primary cosmic rays are charged particles that travel through space at speeds nearly equal to that of light. Most of the particles are protons: nuclei of hydrogen atoms, with a unit positive charge. Other cosmic ray particles are electrons and the nuclei of heavier atoms that have been stripped of all their electrons. Because of their velocities, the particles have very high kinetic energies—many millions or billions of electron volts. However, particles with energies over a billion electron volts are of little interest in space exploration, because they can be observed more conveniently at the Earth's surface.

In addition to galactic cosmic rays, other charged particles of somewhat lower energies move through the outer reaches of the solar system. Some originate in the Sun, some in the solar wind, some in Jupiter's magnetosphere. Some, perhaps, come from sources in a nearby region of the galaxy. The Voyager cosmic ray particle instrument sorts the particles by charge, mass, and energy, and measures the variation in their number at different times, places, and arrival directions. This information makes it possible to study the sources of the various particle populations and the nature of the medium through which they have traveled.

The objectives with respect to cosmic rays require measurements of the energy spectrum of the electrons, and the energy spectrum, elemental and isotopic composition, and the streaming patterns of the nuclei.

Galactic cosmic rays are believed to come from a small number of source regions in our galaxy. The elemental and isotopic abundances among the cosmic ray particles carry information about the process of nucleosynthesis in supernova explosions, as well as information about the average interstellar distance the particles have traversed.

The low energy portion of the galactic cosmic ray spectrum is strongly affected by disturbances that originate in the solar corona. This solar modulation is very far-reaching, but must diminish somewhere well beyond Jupiter's heliocentric distance. One of the important objectives of the cosmic ray particle investigation is to obtain more representative abundances of these cosmic rays by measurements near and beyond the outer boundaries of the modulation region.

Quiet-time observations during the most recent solar sunspot minimum have indicated that the elemental composition of cosmic rays changes substantially at energies below about 15 MeV/nucleon. Oxygen, nitrogen, and helium nuclei become much more abundant. It is an objective of the cosmic ray particle investigation to study this anomalous component of the cosmic ray population and, if possible, to identify its sources. The capability for resolving isotopes is important in meeting this objective. Since the sources are believed to be nearby in the galaxy, the measurement of substantial anisotropies in the cosmic ray flux may provide important identification data.

The cosmic ray particles instrument includes three sets of particle telescopes: the high energy telescope system (HETS), the low energy telescope system (LETS), and the electron telescope (TET). In any telescope, the passage of a cosmic ray particle through a detector results in the liberation of an electrical charge. The charge, which is a measure of the energy lost by the particle in its passage, depends on the particle's charge, mass, and initial energy. This charge is converted to a voltage pulse that can be measured by a pulse-height analyzer. The measurement of a particle event in a telescope involves combining the pulse-height measurements from certain selected detectors with information about the total number of detectors that the particle has penetrated.

The complete instrument package (fig. 15) is mounted on the boom that supports the Science Scan Platform, where the fixed fields of view of all the particle telescopes are unobstructed by spacecraft parts.

The HETS consists of two identical double-ended telescopes: one fixed in the ecliptic plane, and the other perpendicular to it. The HETS can measure the spectra of electrons and the nuclei of all elements from hydrogen to iron over a broad range of energies up to 500 MeV/nucleon. It can resolve individual isotopes through the

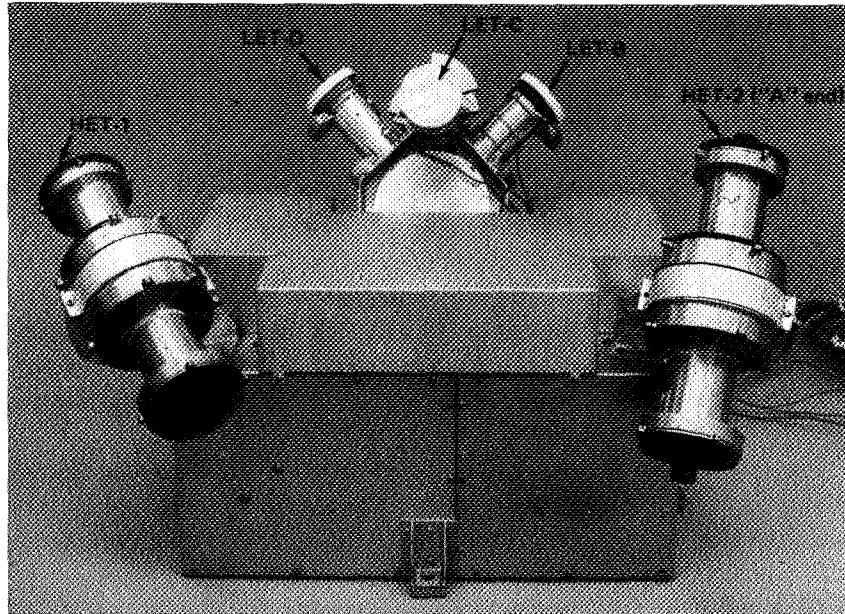


Figure 15.—Cosmic ray particles instrument.

isotopes of oxygen. It can measure the energy of electrons with high precision between 3 and 10 MeV.

The LETS is designed particularly to determine the three-dimensional flow patterns of cosmic rays and to extend the elemental measurements down to very low energies. It consists of four single-ended telescopes. The LETS can distinguish the nuclei of elements from hydrogen to iron down to an energy level of about 1 MeV/nucleon. Isotopes from hydrogen to sulfur can be resolved at energies between about 1 and 75 MeV/nucleon.

There is just one TET in the instrument package. Because electrons are greatly outnumbered by nuclei (which constitute background noise) in the galactic cosmic ray flux, TET is designed to suppress the latter. TET is a single-ended telescope that measures electron energies from about 5 to 110 MeV.

Low-Energy Charged Particle Investigation

Three investigations study charged particles: the plasma particle, low energy charged particle, and cosmic ray particle investigations. The three complement each other in the energy ranges they can

examine, and in the types of data provided. Collectively, they complement the magnetic fields and plasma wave investigations in examining the structure of the planetary magnetospheres and the interplanetary magnetic fields.

The low energy charged particle (LECP) investigation deals with particles of lower energy than does the cosmic ray particle investigation, although there is some overlap. There is a coverage gap between the low-energy end of the LECP range at about 10 000 electron volts and the plasma particle investigation range of 10 to 5950 electron volts. Still, the LECP by itself can provide a great deal of information about the flow velocities and temperatures of hot plasmas when their densities are sufficiently high.

The objectives of the LECP investigation fall into two broad groups: those concerned with particles in the planetary magnetospheres and near natural satellites; and those concerned with particles in the interplanetary environment.

As a result of the Pioneer flybys of Jupiter, the general nature of the Jovian magnetosphere is known. The radiation belts have been located, and their electron fluxes have been observed to be unexpectedly high. The objective here is to fill in details such as the composition, energy range, and angular distribution of the charged particle radiation, to answer such questions as the origin, transport, and loss of the particles, the sources of radio emission, and the effects of the Galilean satellites.

Recent observation of radio emissions from Saturn indicates a magnetosphere exists. Objectives of the investigation during the Saturn encounter are to study the extent of this magnetosphere and to determine the compositions, spectral and angular distributions, and fluxes of particles in various regions. The interaction of the magnetospheric charged particles with the satellites and with the material of the rings will be investigated. The nature of the radio emission will also be examined.

The existence of a magnetosphere surrounding Uranus is also likely. Because the spin axis of Uranus will be pointing very nearly at the Sun in 1986 (encounter date), the interaction of a rotating magnetosphere with the solar wind should differ considerably from those at Jupiter and Saturn.

The objectives of the LECP investigation during the intervals between planetary encounters are concerned with sorting out charged particles by source, composition, energy spectra, flux

intensities, and favored directions. Galactic cosmic ray particles span a very wide range of energies. The LECP investigates the very low end of this range, while the cosmic ray particle investigation achieves better discrimination at higher energies.

The LECP instrument comprises two subsystems whose detector assemblages are mounted in a common pointing apparatus (fig. 16). The detector optimized for the magnetospheric environment is the low energy magnetospheric particle analyzer (LEMPA). The other, designed primarily for the interplanetary environment, is the low energy particle telescope (LEPT). The overlap in energy and intensity measurement ranges is such that each subsystem performs measurements that are important to both environments. Both

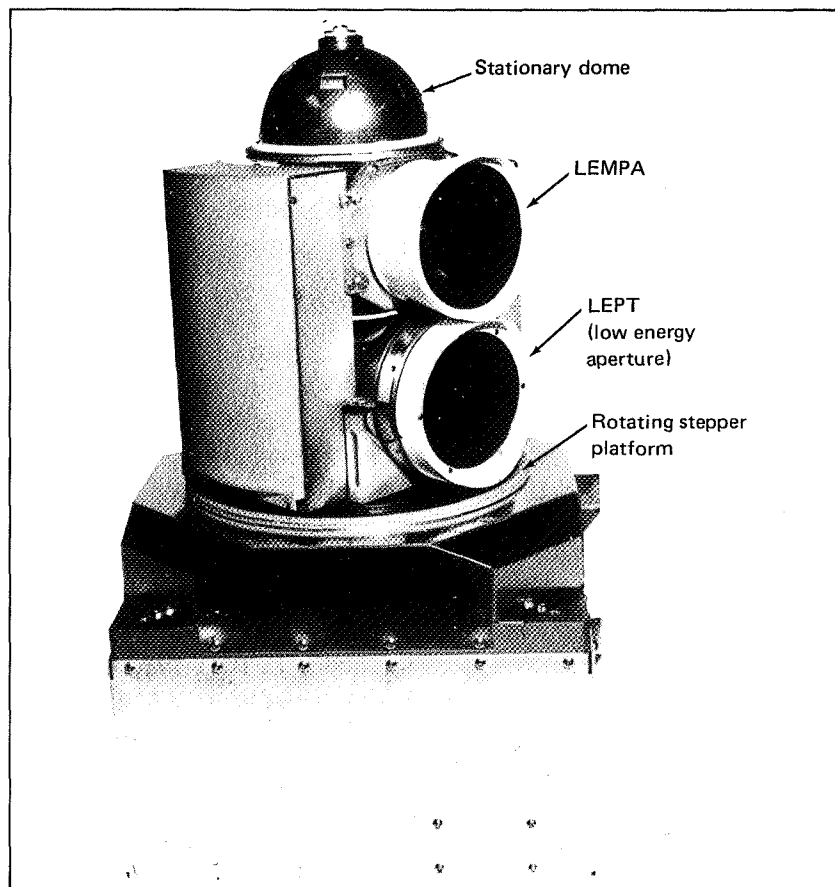


Figure 16.—Low energy charged particles instrument.

operate throughout the mission, except that the LEPT detectors are to be turned off near Jupiter's radiation belts.

An important part of all particle measurements is the detection of anisotropies, or preferred directions, in particle fluxes. The low energy charged particle investigation does this by systematically pointing the axes of the two sensors in successive 45° steps in azimuth. The stepping mechanism rotates in the plane of the ecliptic when the spacecraft is in its usual flight attitude. The two-dimensional anisotropies that can be accurately measured by this directional scanning are sufficient for studies of the interplanetary medium. In order to measure three-dimensional anisotropies of the low-energy electron and proton populations in the planetary magnetospheres, an ingenious arrangement permits two detectors of the LEMPA to make stepwise scans in the direction perpendicular to the ecliptic plane. As the sensor assemblies are stepped through the sequence of azimuths, the unshielded viewing angles of the two sensors rotating at the base of the dome step through a sequence of elevations.

The LEPT is a double-ended array designed to measure the charge and energy distributions of low and medium energy nuclei in environments where the intensity is relatively low.

Plasma Particles Investigation

A plasma is a gas composed of charged particles. The gas as a whole is electrically neutral, or nearly so, but the positive and negative particles can be studied separately. Since the plasma particle investigation is one of three Voyager investigations dealing with charged particles, it is instructive to consider the differences.

The plasma particles have lower kinetic energies than those measured by the cosmic ray particle and low energy charged particle instruments, and there are more of them. Whereas the other investigations are instrumented to count individual particles, the plasma particles investigation is concerned with the collective properties—the plasma's velocity, density, and pressure.

The kinetic energy of a large number of particles can be considered as a group velocity. The instrument measures in the energy range from 10 to 6000 V/charge. This corresponds to velocities up to about 1000 km/sec for protons, and up to about 50 000 km/sec (one-sixth the speed of light) for electrons. By measuring the variation of group velocity with direction, the instrument determines the plasma flow direction.

The flow of a large number of charged particles is, of course, an electric current. The particle density of a plasma can be measured by the current on a collector plate. In principle, the instrument measures the current impinging on a collector plate after the particles with different energies have been sorted out by varying a control grid's retarding potential.

The plasmas that will be investigated are the solar wind and the various regions of planetary magnetospheres. The solar wind, whose average velocity is about 450 km/sec, is highly variable as to velocity, pressure, and density at the Earth's heliocentric distance, and remains so beyond Jupiter's distance.

Jupiter's magnetosphere is a plasma whose composition, flow structure, and density vary greatly in different regions. It interacts with the solar wind that surrounds it, with the Jovian ionosphere which it surrounds, with the Galilean satellites that revolve within it, and with the magnetic fields that traverse it.

Saturn and Uranus probably have magnetospheres as well. The properties and configurations of those plasmas are prime subjects for investigation during encounters with those planets.

The "flux tube" connecting the ionospheres of Io and Jupiter moves through the Jovian magnetosphere. The planned passage of a Voyager spacecraft below Io will provide the opportunity for the plasma particle instrument to investigate the changes in the plasma properties in the vicinity of the flux tube.

Another objective is concerned with the structure and fluctuations of the solar wind to distances of 20 AU. Pioneer observations showed that solar-wind streams do not smooth out their speeds at increasing solar distances. Although the amplitude of the speed fluctuations does decrease, their steepness with respect to time increases. At 4 to 5 AU, nearly all the streams begin with abrupt jumps in the flow speed that are probably shock fronts. The Pioneer instrument could measure the variations in speed, but not the plasma density or temperature variations.

The plasma particles instrument (fig. 17) consists of two Faraday cup plasma sensors. One detector is aligned with the main spacecraft axis that points toward the Earth and approximately into the solar wind. The other detector points laterally, in an orientation that views the rotating flow of the magnetospheric plasma during the Jupiter encounter.

A Faraday cup comprises a collector plate with several grids in front of it, and an aperture that defines the field of view. One of

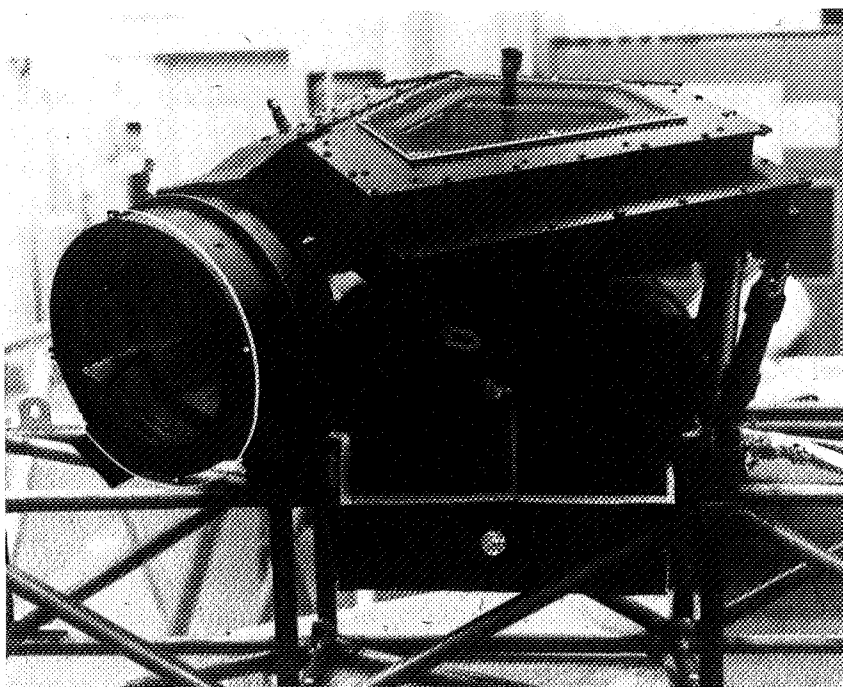


Figure 17.—Photograph of plasma particles equipment.

the grids is a modulator grid; when a retarding potential is applied to it, only those ions with a corresponding range of energy-to-charge ratios are allowed to reach the collector plate. The flux of the selected ions impinging on the collector constitutes a measurable electric current. This measurement can be made for a series of energy-per-charge intervals by systematically varying the retarding potential.

The lateral detector of the plasma particles instrument has two modulator grids. To measure the flow of positive ions, positive potentials are applied to the first grid, while the second is held at ground. For electrons, the first grid is held at ground, and negative potentials are applied to the second grid.

The Earth-pointing detector is a composite Faraday cup. Its collector plate is split into three segments. Each segment is set at an angle of 20° to the main axis (fig. 18), so that they form a flattened tetrahedron. There is a set of grids parallel to each segment, and then the outer surface, which is a tetrahedron with an aperture cut in each face. The composite detector is a direction

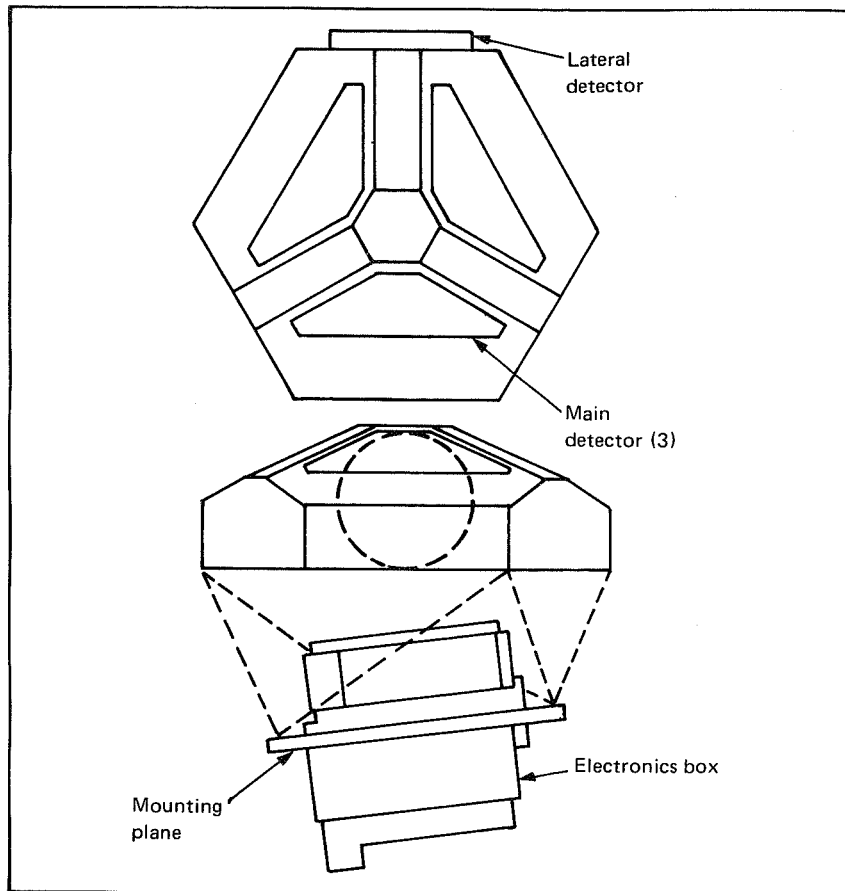


Figure 18.—Schematic diagram of plasma particles equipment.

analyzer: when the same retarding potential is applied to the three modulating grids, the relative currents to the three collector segments provide information about the direction of the plasma flow.

Magnetic Fields Investigation

Magnetic fields are everywhere in the solar system. Some planets have their own magnetic fields, presumably of internal origin. These include Mercury, Earth, and Jupiter. Recent radio data from the IMP-6 satellite indicate that Saturn, too, has a magnetic field. The interplanetary medium is traversed by streams of charged particles that constitute the solar wind, and by the shifting patterns of magnetic fields that they bring with them. The interaction of the

solar wind with the planetary magnetic fields produces the various features of the planetary magnetospheres. Jupiter's inner satellites, whose orbits lie within its magnetosphere, must likewise interact with it. Some of the satellites of Saturn and Uranus may do the same. Finally, the solar wind must interact with the particles and magnetic fields of the interstellar medium. The zone where this takes place, the heliopause, is at an unknown distance from the Sun.

The magnetic fields investigation will gather data on all the fields encountered in the mission. Because of the extreme differences in the strengths of the planetary and interplanetary magnetic fields, the instrument employs both a low-field and a high-field magnetometer system.

An important objective of the investigation is to measure the magnetic fields of Jupiter, Saturn, and Uranus. Since Jupiter's field has already been measured by magnetometers on the Pioneer 10 and 11 missions, the new measurements at that planet can provide a data base for studying any long-term changes in the field. Pioneer 11 is expected to make the first measurements of Saturn's magnetic field as well, in September 1979. The planet Uranus is also believed to have a strong magnetic field, although the IMP-6 observations of radio emissions coming from that direction are not free of ambiguity.

Although the structure of Jupiter's inner magnetosphere is fairly well understood, the three-dimensional structure of the outer region needs additional observations. The structure of Saturn's magnetosphere is still unknown, and the two mission traverses should define its general features. The presumed magnetosphere of Uranus should have a particularly interesting structure because of the orientation of the planet's pole in the Sun's direction at the time of encounter.

In order to increase our understanding of the basic physical mechanisms involved in the dynamics of the magnetospheres of rapidly rotating planets and in their interactions with the solar wind, the magnetic fields instrument will acquire the data for correlative studies with the other particles and fields investigations.

Investigating the interactions of satellites with the planetary magnetospheres is another objective. Jupiter's magnetosphere includes the orbits of Amalthea and the four Galilean satellites. Io, which controls the emission of radio bursts of decametric wavelengths from Jupiter's ionosphere, must exert this control

through the magnetosphere. The plasma sheath (ionosphere) surrounding Io evidently is electrically connected to the Jovian ionosphere through a "flux tube" along the lines of force of Jupiter's magnetic field. The scheduled passage of one of the spacecraft through the flux tube should permit the investigation of this interaction. Io may possibly have an internal magnetic field as well, and this will be considered in the analysis of the magnetic field data. If Ganymede has an internal magnetic field, the planned close encounter should permit detection of its interaction with the magnetosphere.

Saturn's largest satellite, Titan, revolves at a distance of about 20 Saturn radii from the planet. Saturn's magnetosphere probably extends that far, at least during undisturbed solar wind periods. Since Titan has a rather dense atmosphere, the interaction of the satellite with its environment (whether it be the magnetosphere or the solar wind) will be particularly significant. The close approach distance of 4000 km should allow a thorough observation.

The magnetic fields instrument consists of a high-field magnetometer (HFM) system and a low-field magnetometer (LFM) system. Each system contains two identical triaxial fluxgate magnetometers that measure the magnetic field intensity along three orthogonal axes simultaneously, producing a direct vector measurement. One LFM is located at the end of a 13-m boom, where the magnetic field of the spacecraft is not expected to exceed about 0.2 gamma. (One gamma equals 0.000 01 gauss, which is the unit of magnetic field strength. The average geomagnetic field strength at the Earth's surface is about 0.5 gauss, or 50 000 gamma.) The other LFM is located about 5.6 m in from the end of the boom. With simultaneous measurements using this arrangement, it is possible to separate the spacecraft field analytically from the ambient field. The two high-field magnetometers are located about a meter apart on the truss that supports the magnetometer boom.

Plasma Wave Investigation

Plasma waves are low-frequency oscillations that have their origins in instabilities within plasmas. As we have seen in a previous section, the plasma particles investigation provides information about the bulk properties and composition of the gases of charged particles—the plasmas—that constitute the solar wind and the planetary magnetospheres. When examined more closely, plasmas exhibit

instabilities of several kinds. There is turbulence in the flow of the particles, and the electrically neutral plasma carries local concentrations of positively and negatively charged particles. When these instabilities become oscillatory, plasma waves are generated.

Plasma waves can be categorized as either electrostatic oscillations or as generalized electromagnetic waves of very low frequency. The Voyager plasma wave investigation measures only the electric field component. Although the frequencies of interest extend from about 0.01 Hz to about 100 kHz, the plasma wave instrument itself detects only the range of frequencies between 10 Hz and 56 kHz. The Voyager magnetometer can measure the magnetic vectors of electromagnetic plasma waves below 10 Hz, and the planetary radio astronomy instrument measures plasma waves with frequencies over 56 kHz.

The plasma ions and electrons both emit and absorb plasma waves. These particle-wave interactions are known to affect the magnetospheric dynamics of the outer planets and the properties of the distant interplanetary medium, but they have not been directly observed in these regions. In general, they can only be observed by flying spacecraft through the interaction regions. Electrostatic plasma waves only propagate for short distances, and the propagation of electromagnetic plasma waves is also greatly restricted when the frequency is lower than the gyrofrequency (cyclotron frequency) of the ions and electrons.

A main objective is to study the role of wave-particle interactions in determining the dynamics of the magnetospheres of the outer planets. Some of the effects are the heating of solar wind particles at the bow shock (the shock front sunward of the magnetopause), the acceleration of solar-wind particles that produce high-energy trapped radiation, and the maintenance of boundaries between the rotating inner magnetosphere and the streaming patterns in the outer regions.

Another objective is to study the effect of wave-particle interactions on the mechanisms by which the inner satellites of the major planets interact with the rapidly rotating magnetospheres. The control of Jupiter's decametric radio bursts through the coupling of Io's ionosphere with the planet's magnetic field is a leading instance.

Detection of lightning discharges in the atmospheres of Jupiter and Saturn would be very significant. The plasma wave investigation will search for "whistler" signals that escape into the mag-

netosphere from such discharges. The characteristic descending whistle that is detected from lightning on Earth is due to the frequency dispersion of group velocities when the propagation is along magnetic lines of force: the higher frequencies of a broadband pulse arrive at the receiver in advance of lower frequencies.

The plasma wave investigation and the planetary radio astronomy investigation share the same basic sensors: a pair of antenna elements arranged at right angles that are extended after launch to a length of 10 m (fig. 19). Whereas the planetary radio astronomy investigation uses the antenna elements as two orthogonal monopoles, the plasma wave investigation uses them as a balanced V-shaped dipole. The latter arrangement is the same as the familiar "rabbit ears" on home TV. The effective length of the dipole is half the distance between the outer ends of the elements, or 7 m.

As the drawing indicates, a single electronics box containing all the signal processing equipment for the plasma wave investigation is mounted above the planetary radio astronomy instrument, near the root of the antenna. After amplification, the signals can be processed either by a 16-channel spectrum analyzer or by a waveform amplifier and digitizer.

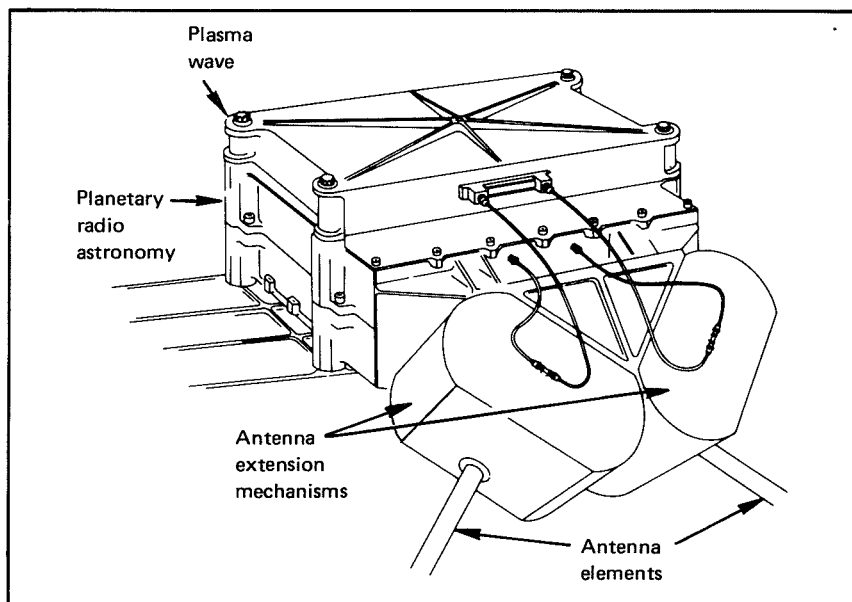


Figure 19.—Plasma wave equipment.

Planetary Radio Astronomy Investigation

This investigation will measure the radio emissions of Jupiter, Saturn, and possibly other planets, both during planetary encounters and cruise. The power and time history of the emissions will be measured in 198 discrete narrow-frequency bands in the range from 1.2 kHz to 40.5 MHz. A distinctive feature is the measurement of the polarization of the emissions, with the power in the right-hand and left-hand circular polarizations determined separately.

Broad-band planetary and solar radio emissions of thermal origin are noncoherent and unpolarized. The electromagnetic waves have random phase relationships and vibrate in all planes. On the other hand, nonthermal planetary emissions cover narrow frequency bands and are largely coherent. When the waves at a given frequency are in phase, it is possible to determine the direction of their circular polarization: the plane of vibration rotates either clockwise (right-handed) or counterclockwise (left-handed) as successive crests arrive at the antenna.

Until the recent observation of nonthermal radio emission from Saturn (and possibly also from Uranus), all examples of planetary nonthermal emission came from the Earth or Jupiter. The polarization of terrestrial emissions is unknown—indeed, the Voyager planetary radio instrument will have the first opportunity to observe it. Jupiter's nonthermal emissions have a strong right-handed polarization at most observed frequencies.

While Earth-based radio astronomy observations commonly include polarization measurements, the Voyagers will be the first spacecraft to do it.

A major set of objectives is to locate as closely as possible the sources of planetary emissions at kilometric, hectometric, and decametric wavelengths; and to seek explanations of their origin by correlation with data from other Voyager investigations. The powerful sporadic bursts from Jupiter that are modulated by the satellite Io are mainly decametric.

It is conventional in radio astronomy to classify emissions by their wavelength bands. The planetary radio emissions of particular interest to this investigation are kilometric, hectometric, and decametric. A wavelength of 1 km corresponds to a frequency of 300 kHz, a hectometer to 3 MHz, and a decameter to 30 MHz.

The sources will be located mainly by the changes in signal strength at the various wavelengths in the course of the planetary encounters. The signals from a given source region can be expected to peak perceptibly at the closest approach of the spacecraft. If a source is in the magnetospheric belt or near a satellite, that fact should be readily determined.

An important objective is the investigation of the relationship of a planet's radio emissions to its satellites. Although Io is apparently the only satellite influencing Jupiter's decametric emissions, there may be relationships to Amalthea and to the other Galilean satellites that are observable only from space.

A last objective is to make use of the Voyager cruise trajectories to compare the detection of radio emissions from different perspectives in space. Records over two decades of Earth-based observations of Jupiter's decametric emissions appear to show a pronounced beaming of the emissions. Jupiter's axis is inclined only 3° , yet the emission probability varies by a factor of 5 with the planet's position in orbit.

Although evidence of beaming can be assembled from the comparison of observations made at one location (Earth) at widely different times, it requires simultaneous observations from different viewpoints to define the actual beam patterns. During much of their missions, the two Voyager spacecraft will provide data from well-separated observing stations to compare with the Earth observations.

The radio emissions are received by two 10-meter antennas. They are employed, for the planetary radio astronomy experiment, as separate monopoles oriented 90° apart. While unpolarized coherent signals received by the two monopoles will be in phase, one monopole will receive circularly polarized signals somewhat advanced in phase with respect to the other. A pair of 90° hybrid couplers in the instrument determines which monopole leads in phase, and thus whether the polarization is right-handed or left-handed.

There are separate receivers for the low-frequency band and the high-frequency band. Because of the extreme sensitivity required by the investigation, it is necessary to avoid the frequency of the spacecraft power supply (2.4 kHz) and all of its harmonics. To accomplish this, the low-frequency receiver is limited to a bandwidth of 1 kHz, and the observing frequencies are spaced at

intervals of 19.2 kHz. There are thus 70 discrete observing frequencies (each 1 kHz wide) in the low-frequency band.

The high-frequency band receiver has a 200-kHz bandwidth, and the 128 observing frequencies are spaced at intervals of 307.2 kHz.

Appendix A

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