Ulysses spacecraft takes a new look at the Sun

The first spacecraft to be propelled outside the planetary plane of the ecliptic, Ulysses will give us a unique look at our nearby star, by orbiting the poles of the Sun. Marsha Freeman reports.

The European-built Ulysses spacecraft was launched on Oct. 6 from the payload bay of the U.S. Space Shuttle orbiter Discovery, to begin a five-year mission to study the Sun. By doing so from a position nearly perpendicular to the planetary plane of the ecliptic for the first time, Ulysses will provide a new look at our nearby star.

For millennia, man awoke each morning to the assurance of the one constant object in his environment: the Sun. Until this century, it was assumed that the Sun's light and radiant energy were unchanging. Indeed, the energy released by the Sun is called the "solar constant." Astronomers did not initially realize that the Sun is but one of a vast number of highly active stars.

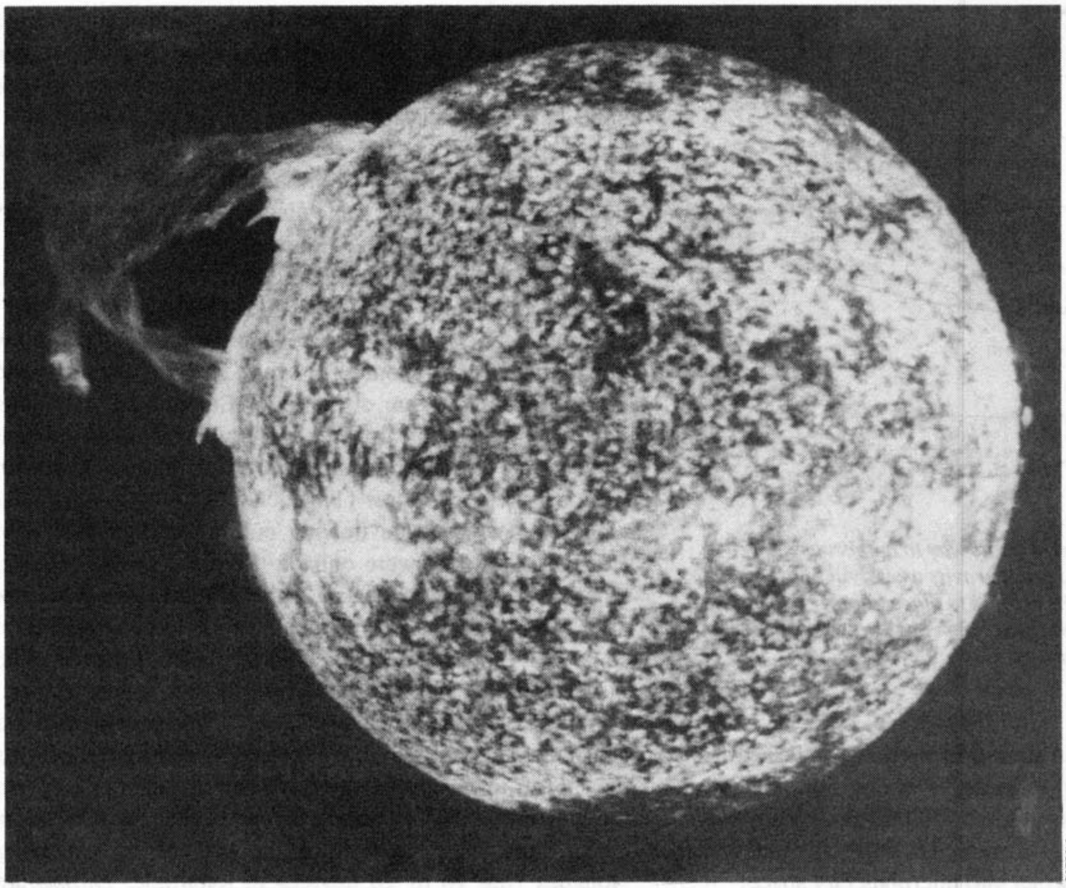
But in 1973, X-ray telescopes aboard the world's largest space station, Skylab, showed us a new, active Sun. Observing it during a period of intense solar activity in the Sun's 11-year sunspot cycle, scientists saw cataclysmic eruptions of plasma, or hot ionized gases, spewing violently from near the Sun's surface into interplanetary space.

Sunspots were discovered to be concentrations of lower temperature gas and magnetic energy, correlated with the production of violent solar flares, and prominences made up of plasma filaments connecting these concentrations of magnetic energy of opposing polarity. Scientists watched as the sunspots moved from halfway between the poles and the equator of the Sun, at 45 degrees latitude, toward the equator, as it prepared for the 11-year reversal in magnetic polarity. The active Sun introduced a new oxymoron into the language of astronomy: "variations in the solar constant."

Changes in the release of energy from the Sun, particularly in the form of the charged particles which make up the 1 million-mile-per-hour solar wind, have long been recognized as responsible for various effects on the Earth. As these particles collect in the Van Allen Belts which surround the Earth and protect it from harmful levels of radiation, they are periodically released in bursts into the ionosphere, producing the Aurora Borealis, or Northern Lights.

These releases can also affect the electromagnetic activities of people on this planet, as was witnessed earlier this year when bursts of electromagnetic energy caused surges in electric power transmission lines, blacking out large parts of Canada. It has also been suggested that the electromagnetic radiation from particularly the large U.S. and European electricity transmission systems, in turn, affects the energetic releases into the ionosphere.

For many years, scientists have tried to correlate sunspot and other solar activity with changes in the climate on Earth. Between 1645 and 1715 there was an unusual lull in sunspot activity. Named after the French astronomer who studied this, the period is known as the Maunder Minimum, or alternatively as the "mini-ice age." There was an estimated 1°C drop in average global temperature because of the lull in solar activity, which caused increased glaciation, bad crops, and famine.



Skylab's telescopes revealed an active and spectacular Sun. This flare, photographed on Dec. 19, 1973 and extending 367,000 miles across the solar surface, clearly shows the twisted plasma structure along the magnetic field lines produced by the quickly rotating solar sphere.

It is particularly important for space scientists today to understand and monitor the activity of the Sun, because sudden intense releases of high-energy particles and radiative energy in outer space, where people are not protected by the Earth's radiation belts and atmosphere, could be life-threatening. The Apollo missions were carefully planned during a period of solar quiescence, and while the astronauts were on their way to the Moon, or walking on its surface, astronomers on Earth were on constant watch for unexpected solar flares, in order to be able to send a warning to the explorers to take refuge in a magnetic "storm cellar" if necessary.

Even Earth-orbiting spacecraft are affected by changes in solar activity. On March 6, 1989, an extraordinarily fierce solar flare erupted from the surface of the Sun. The energy of the flare was estimated to be comparable to the total energy consumed in mankind's entire history. Eight minutes and 20 seconds later, the first pulse of X-rays and other radiation swept past the Earth. Solar radiation detectors on the Solar Maximum Mission satellite and the GOES weather satellite were quickly saturated, but did recover.

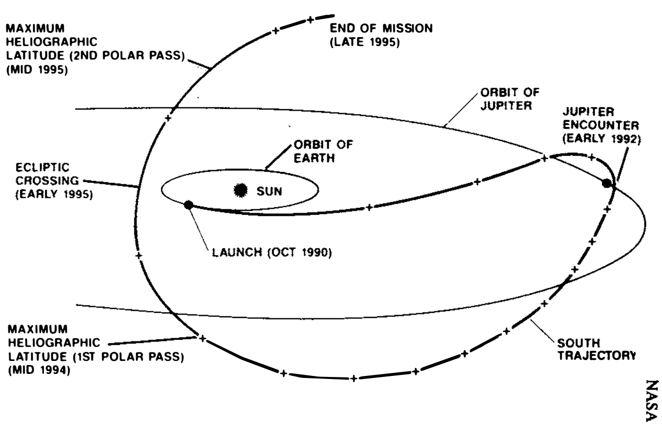
Two days later, the Earth was engulfed by the flare-induced shock wave in the solar wind, and the ensuing geomagnetic storm heated up and expanded Earth's atmosphere enough to increase the drag on over 5,000 Earth-orbiting satellites which were knocked out of position. From that incident, Solar Max dropped nearly a kilometer in altitude.

During its five-year mission, the Ulysses spacecraft, which was built by Dornier GmbH of West Germany for the European Space Agency, will study the Sun itself, the magnetic fields and streams of particles generated by the Sun, and the interplanetary space above the Sun. Combined with the data from Skylab, the Solar Maximum Mission, and other spacecraft, along with ground-based observations which have all looked at the Sun "head-on"—from within the plane of the planets—the Ulysses data, from a viewpoint nearly perpendicular to the plane of the ecliptic, will give us our first "three-dimensional" look at the Sun (**Figure 1**). The importance of this difficult task, we shall examine below.

The solar wind

Until man could send spacecraft above the distorting and protective atmosphere of the Earth, it was thought that our planet traverses a vacuum as it orbits the Sun. The observations of Explorer 1, launched in January 1958, revealed that the Van Allen Belts surrounding the Earth capture high-energy particles from space, most likely from the Sun. In 1962, the Mariner 2 spacecraft verified earlier theories that the Sun

FIGURE 1



The Ulysses spacecraft is now on its way to a February 1992 encounter with Jupiter. A Jovian gravity assist will boost it south of the planetary plane of the ecliptic to place it under the Sun's south pole in mid-1994. One year later, it will view the Sun from above its north polar region.

continuously produces a stream of particles, released from the corona or outer halo-like layer of the Sun. Scientists estimate that this layer is at least 500,000 times fainter than the Sun itself. The Earth is immersed in the solar wind, which is an extension of the corona into interplanetary space.

The thin corona was seen to have "holes" during periods of minimum activity in the 11-year sunspot cycle, near the poles of the Sun where the plasma is not wrapped tightly around magentic field lines, and from which few X-rays are emitted. The solar wind spewing from the corona is visible from Earth-based telescopes during eclipses, when the Moon blocks out the bright solar disk and the very thin corona can be observed. Skylab's telescopes were able to provide data about these coronal holes without waiting for eclipses, because they could "look" at the Sun's X-ray emission, not just the visible light. This revealed that the holes move away from the poles and toward the equator in the active parts of the solar cycle. Although the solar wind blows continuously, its density and velocity are always changing.

It has been difficult to examine the creation and propagation of the solar wind up until now, because the Sun's equator, which is what you can observe from the ecliptic plane, is whirling around at over 4,000 miles per hour, rotating on its axis every 27 days. It is pulling both high- and low-speed streams of plasma along with it, creating a complex of interactions which dominate the physics that can be observed.

A teaser on how interesting the solar wind will be from outside the plane of the ecliptic was noticed in 1988. NASA scientists examining data from 1985 collected by the Pioneer 10 and 11 spacecraft on their way out of the Solar System, and from Voyager 2, which was then 2 billion miles from the Sun, discovered variations in the solar wind. Scientists knew that the solar wind does not slow down with distance, as there appears to be no dissipation of energy in the form of heat. Pioneer 10 and Voyager 2 were at varying distances from the Sun, but approximately at the ecliptic plane. Pioneer 11, however, was about the same distance as Voyager 2, but 15 degrees higher in latitude, or above the ecliptic plane.

Before 1985, both Pioneer 10 and Voyager 2 measured periodic gusts in the solar wind called "high-speed streams." These energetic particles were seen to speed up and then slow down dramatically about once every 27 days, or one period of rotation of the Sun on its axis. But in June 1985 this wind stream pattern stopped and the winds slowed down at Voyager 2's distance of 2 billion miles, though no slowdown was measured by Pioneer 11, which was farther away. Eventually, the winds were flowing only about half as fast at Voyager 2 as they were outside the plane of the ecliptic, where Pioneer 11 was located. Three months later, in August 1985, the solar wind slowed and the high-speed streams also stopped at Pioneer 10, on the ecliptic plane, but at twice the distance of the other two spacecraft.

These changes in the solar wind, which are part of the sunspot cycle, were discovered to be related to the fact that the "holes" in the corona move over the 11-year cycle. When the Sun approaches the solar maximum, these coronal holes creep from the poles toward the equator by extending "tongues" out 10 or 20 degrees in longitude. During the quiescent period of solar minimum, the holes creep back toward the poles. The solar wind apparently blows out fastest from these lower-density holes at the poles.

It is expected that when Ulysses can view the Sun from above and below the poles, it will provide a simpler, and certainly different, view of the origin and propagation of the solar wind, as it is believed that above the poles, the plasma flow should be of more uniform speed and parallel to the radially extended magnetic field lines, rather than twisted into complex structures.

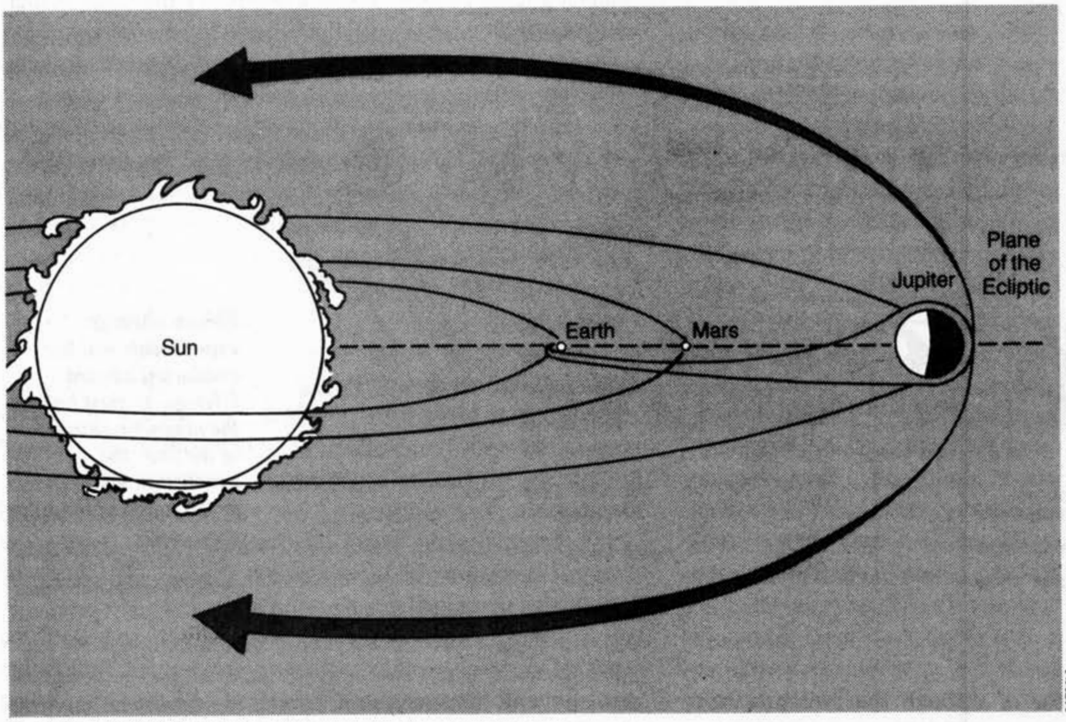
The Sun's magnetic fields and radiation

Similarly, the magnetic fields generated by the rotating plasma of the Sun, which are created by the power currents of electricity flowing in the interior of the Sun, co-rotate with the star. In the equatorial region of the ecliptic plane, the magnetic field lines take on the appearance of a water stream tossed out by a garden sprinkler.

However, at the poles, the magnetic field lines extend radially outward from the Sun, because these regions are less affected by the Sun's rotation. The same is true for the magnetic fields around the Earth.

Because the sunspot cycles are so intimately connected to the changing concentrations of magnetic energy in the Sun, observing the poles should shed light on these fundamental solar processes.

FIGURE 2



The two-spacecraft International Solar Polar Mission: According to the original plan, two spacecraft, launched simultaneously from the Shuttle, would have orbited the poles of the Sun at the same time. Thus, a genuine three-dimensional view of the Sun would have been possible.

For decades, astronomers proposed that changes in solar activity, particularly sunspots, changed the amount of radiation emitted by the Sun, or the "solar constant," and that this affects the Earth's weather. The Solar Maximum Mission satellite proved this to be the case. Launched on Feb. 14, 1980, Solar Max continuously monitored the output of the Sun, in a spectral range from the far ultraviolet to the infrared. Though a failure of its attitude control system in late 1980 reduced the pointing capabilities of the craft, and therefore the precision of the data, it was repaired by Space Shuttle astronauts in 1984 and continued its mission.

Total radiant output of the Sun decreased slightly between 1980 and 1985, during solar minimum, and then started to increase. Since scientists assume that since the actual amount of energy being produced through the nuclear fusion process is constant, it would mean there is some mechanism in the Sun through which energy is stored in the atmosphere during periods of quiescence.

Studying the data over seven years, astronomers found a convincing correlation between the degree of sunspot activity and the energy emitted from the Sun. A treasure trove of extremely detailed data was also acquired regarding the magnetic structures which organize the sunspots. Solar Max measured the intensity and polarity of magnetic energy above sunpsots and helped provide explanations for some of the mystery of how these concentrations of magnetic energy form.

Unrealized plan for a two-spacecraft mission

Astronomers have been anxious to take a look at the Sun from outside the plane of the ecliptic for decades, because of the difficulties of studying the most interesting and important solar phenomena from a head-on view. The first mention of an out-of-the-ecliptic mission appears to have been during a meeting of the American Geophysical Union in 1959.

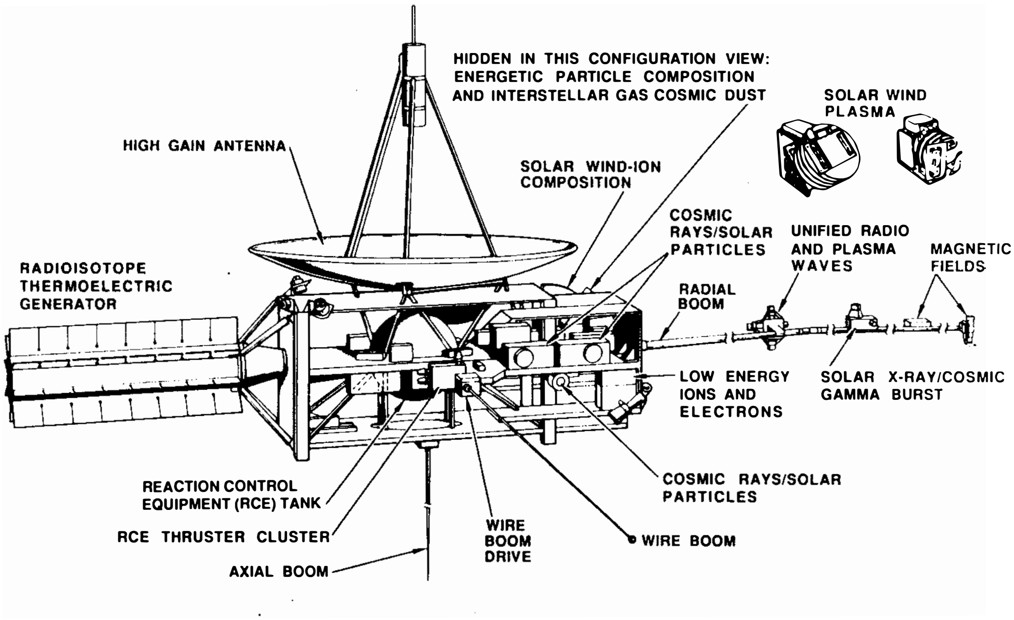
In the 1960s, the results from a series of Pioneer missions showed that the heliosphere (the interplanetary region influenced by the energy output of the Sun) in the vicinity of the Earth is highly structured, increasing the interest in an out-of-ecliptic trajectory for a spacecraft.

By 1974, a dual-spacecraft mission, to observe both solar poles simultaneously, was conceived by a joint U.S.-European team, which was reviewed at a symposium the following year (**Figure 2**). In 1976, the European Space Agency (ESA) and NASA started planning the International Solar Polar Mission (ISPM), and one year later, the two agencies issued a joint announcement of opportunity to the scientific community to develop concepts for the instruments that the two spacecraft would carry to the solar poles.

Because no propulsion system has been developed to give a spacecraft enough energy to do this directly from Earth orbit, a plan was proposed to fly such a craft around the largest planet in the solar system—Jupiter—for a "gravity assist" to push it out of the ecliptic plane.

One early concern was the extent of damage a spacecraft

FIGURE 3



Eleven scientific experiments will be conducted aboard Ulysses, to shed light on the magnetic structures of the Sun, the production and propagation of the solar wind, and characteristics of the interplanetary medium.

might suffer passing near or through the radiation belts around Jupiter. After the successful Pioneer and Voyager missions, however, engineers were confident that a Jupiter gravity assist for a solar polar mission was possible.

In 1978 the Jet Propulsion Laboratory (JPL) in California released a profile for such a complex mission, and 200 scientists from 65 universities and research centers in 13 countries were chosen to participate, with 17 experiments identified for the mission. The ISPM plan consisted of simultaneously launching two spacecraft from the Space Shuttle in 1983, to slingshot around Jupiter, and then approach the Sun from opposite poles. The report stated that no spacecraft had yet "ventured off the ecliptic plane, by more than 15 degrees" in latitude relative to the Sun.

The four-year mission called for the two spacecraft to arrive at Jupiter in May 1984, within days of each other, and for NASA to build one craft, and the European Space Agency the second. The estimate was that the U.S. part of the mission, which included the cost of the Shuttle launch and the tracking of the two craft by NASA's Deep Space Network, would be $141 million in 1977 dollars.

The JPL plan explained that the mission "will take a subject which is currently two-dimensional in its outlook and bring it into three-dimensional reality." The mission was to study all solar latitudes several times and simultaneously in both solar hemispheres, in three and a quarter years.

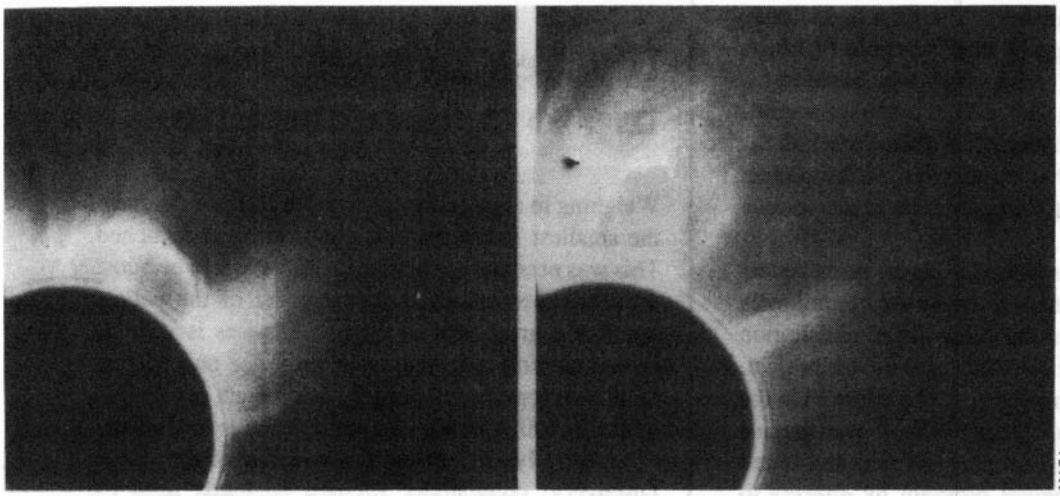
The scientific experiments proposed were designed to study the Sun, interstellar space, and the solar wind. The enormous distance between the spacecraft and the Earth would allow for measurements of distant astronomical phenomena with less interference from the terrestrial environment than had hitherto been possible.

For example, instruments were proposed to study sources of gamma rays, such as neutron stars, pulsars, and quasars. A zodiacal light experiment was outlined to observe the intensity, color, and polarization of remote light sources, such as stars, galaxies, and light scattered by the interplanetary dust cloud. These measurements would produce a three-dimensional picture of the distribution of the particles in the Solar System.

It was proposed to study the temperature, velocity, and density of the interstellar gas, along with a cosmic dust experiment designed by scientists at the Max Planck Institute for Nuclear Physics in Germany. This experiment would detect and record the mass, speed, flight direction, and electric charge of cosmic dust.

To study the Sun, an array of complementary instruments was put forward for each of the two spacecraft. Several instruments were proposed to study the solar wind, including a mass-separating experiment which could separate ions that enter the instruments according to their mass charge, to measure the wind in three dimensions. A plasma spectrometer would analyze electrons, protons, alpha particles, and various charged states of oxygen, silicon, and iron as they make up the solar wind, at all latitudes of the Sun.

The magnetic fields of the Sun, as well as of Jupiter and the interplanetary medium, would be measured by instruments to reveal their structure and dynamic properties. An X-ray ultraviolet telescope and white-light coronagraph were instruments proposed by the ISPM study, to observe the Sun.



NASA

These two photographs, seen with the aid of Solar Max's coronagraph, were taken 49 minutes apart. In the first picture, a solar prominence is forming out of the diffuse solar corona. In the second picture, the looping structure of the prominence is clearly visible.

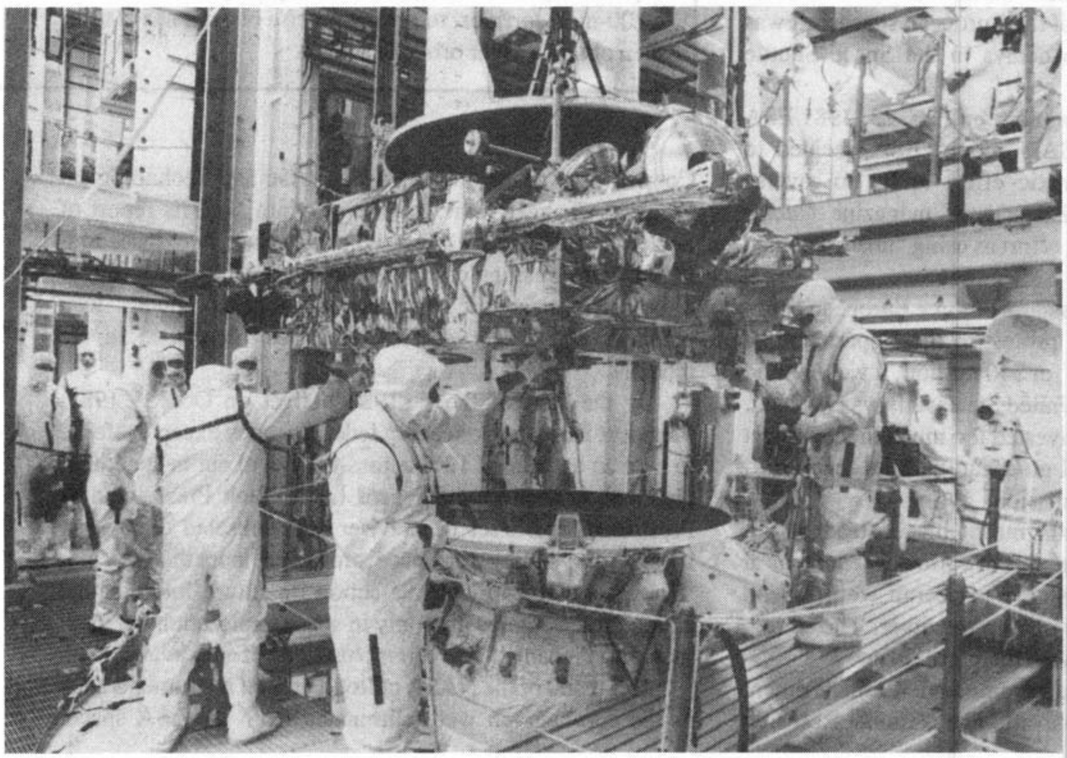
These two experiments together would provide images of layers of the Sun's atmosphere, from the chromosphere to the outer corona. They would help determine the dimensions of the corona and its relationship to the surface of the Sun.

Budget-cutters wrecked the original plan

On March 29, 1979, a Memorandum of Understanding was signed by NASA and ESA for the International Solar Polar Mission to be launched from the Space Shuttle in 1983. TRW, Inc. was selected as the contractor for the American spacecraft—but this agreement did not last long.

When the last Carter administration budget, for fiscal year 1981, went to Capitol Hill in the spring of 1980, it was proposed that the Solar Polar Mission be postponed from 1983 to 1985, to save $43 million.

Congress only made the situation worse. In the first week of May, the House Appropriations Committee stated that "NASA has not done its part to balance the budget," and voted to terminate the ISPM project. The committee complained that when asked to cut its budget, NASA manage-



On July 31, the Ulysses craft was lowered for mating with the Payload Assist Module in the Vertical Processing Facility at the Kennedy Space Center.

ment did not cancel anything, but just deferred programs.

The Europeans were not amused. The ESA had already spent $30 million in the design of their spacecraft (NASA had already spent $60 million), and stood to be liable to the Dornier firm for the remaining $50 million to build the craft. In a letter to then-NASA administrator Robert Frosch, ESA director Roy Gibson stated that cancelation of the project would kill as much as 25% of Europe's total space science effort.

The Carter White House reportedly began firing letters off to Congress to convince them to reject the committee's recommended termination, but the delay the administration insisted upon was expected to *add $100 million* to the project, nearly doubling the initial estimated cost. An editorial in the June 9, 1980 *Aviation Week and Space Technology* magazine criticized the disregard for our European partners and stated that ESA had rescued the original program by *offering* to build the second spacecraft, when NASA could not get the money for it. The effort to kill the U.S. spacecraft was temporarily beaten back, through a diplomatic mobilization by the Europeans.

But Ronald Reagan was elected President in November of that year, and his first budget went to Capitol Hill for FY1982 in the winter of 1981, with the recommendation from the Office of Management and Budget that NASA reduce its space science programs from the $756 million recommended by the Carter administration, to $597 million. The space agency had to choose between keeping the Galileo spacecraft to Jupiter and the Magellan spacecraft to Venus on schedule, or building its spacecraft for ISPM. NASA unilaterally decided to eliminate its half of the two Solar Polar spacecraft. The launch of the European spacecraft was also pushed to 1985, due to delays in the Space Shuttle program.

At a tense meeting in New York on Feb. 23, 1981 ESA representatives rejected NASA's action. ESA decided to launch a high-profile diplomatic effort to try to reverse NASA's decision. The British science magazine *Nature* characterized ESA's lobbying effort as using "unaccustomed undiplomatic language."

Early in March the ambassadors of three European countries took an official note of protest to the Department of State. ESA made an offer that for $40 million, it would build the second spacecraft for the United States; this was rejected. Finally, ESA decided it had invested too much in the project to cancel it, and that it would go ahead with its spacecraft, resulting in a one-spacecraft mission.

The one-spacecraft mission meant that instead of obtaining simultaneous measurements of various phenomena at each of the Sun's poles, the single spacecraft would spend nearly a year going from one pole to the other. The stereoscopic nature of the mission was, therefore, lost.

Congressional committees recommended reinstatement of the NASA program, to no avail. The National Research Council Committee on NASA Scientific and Technological Program Changes reviewed the program, and its report of September 1981 states that "the complete two-spacecraft ISPM, with imaging capability on the NASA spacecraft, is a powerful scientific investigation that is sound, well planned, and meets all the objectives" described in the report.

By the start of the FY1982 budget on Oct. 1, 1981, President Reagan asked every federal agency except Defense to take an additional 12% across-the-board cut in spending. National Academy of Sciences head Frank Press, who as President Carter's science adviser had counseled against any increased spending for space programs, nonetheless said, "The potential harm of our action on future international cooperative ventures, not only in space exploration but in all matters . . . cannot be overemphasized." To no avail.

As a result of the NASA pullout, crucial instruments such as the coronagraph were eliminated from the ESA space-

Ulysses' five-year trip to explore the Sun

Weighing in at just over 800 pounds, Ulysses is one of the smallest interplanetary spacecraft ever launched. This was necessary, because in order for it to be boosted nearly perpendicular to the plane of the ecliptic requires a great deal of energy. Ulysses is now the fastest-moving man-made vehicle in the universe, on its way to Jupiter, traveling 45 kilometers per second, or nearly 100,000 miles per hour, relative to the Sun.

After Ulysses left the payload bay of the orbiter Discovery, commander Richard Richards fired the Shuttle's Orbital Maneuvering System engines to move the Shuttle away from the spacecraft. One and a half hours after deploy, the two-stage Inertial Upper Stage (IUS) engine was attached to Ulysses, and then a three-stage Payload Assist Module propulsion system was fired.

Before that could be done, however, the exact position of the spacecraft and attached IUS in the payload bay had to be determined, because even if it had moved a fraction of an inch during ascent to orbit, the IUS navigational data would have to be changed. A small navigational error in Earth orbit propagates into a significant error over the nearly half-billion-mile trip to Jupiter. Ulysses must approach the giant planet within a 100-mile corridor, to get the precise boost it needs to then obtain a polar orbit at the Sun.

In addition to knowing the precise position of the spacecraft in the Shuttle orbiter, the navigational unit in the Inertial Upper Stage was tested to make sure it agreed with a similar unit in the orbiter. Ground controllers observed both the orbiter and IUS data to make sure there were no differences in how the two spacecraft systems believed they were oriented in space. The IUS must have precise attitude data to correctly compute the seconds the engines must burn for the proper Jupiter trajectory.

Shuttle commander Richards calculated before the mission that the mathematical targeting for Ulysses' trajectory is equivalent to a golfer hitting a 360-mile hole-in-one.

Ulysses' flight plan

In February 1992 Ulysses will arrive at Jupiter, where it will take measurements of magnetic fields and structures, and other phenomena, similar to its mission activities at the Sun. It will fly past Jupiter at about 30 degrees north Jovian latitude, and the planet's gravity will push the spacecraft into a downward dive away from the ecliptic plane.

In June 1994, the spacecraft will reach 70 degrees south solar latitude, beginning its transit of the Sun's polar regions. Ulysses will spend about four months south of that latitude at a distance of about 200 million miles from the Sun, or more than double the distance between the Sun and the Earth. The spacecraft will observe the Sun from a unique vantage point, but not up close.

In February 1995, Ulysses will cross the equator of the Sun, followed by a four-month pass of the Sun's northern polar region, beginning in June of that year. The official end of the mission is Sept. 30, 1995.

The Deep Space Network, which is receiving data from a number of interplanetary spacecraft including Magellan which is orbiting Venus, and Galileo on its circuitous way to Jupiter, will receive Ulysses' data for eight hours a day. During this time, the spacecraft will transmit data from the previous 16 hours stored on tape recorders.

Built into the timeline for Ulysses was an initial trajectory correction 10 days after launch, but it was reported from tracking data that the craft will probably not require the correction.

Spectacular data expected

While on its journey to Jupiter, and then from Jupiter back toward the inner Solar System and to the Sun, Ulysses will be sampling and measuring the energetic and particular aspects of interplanetary space. It will also reveal more of the fantastic dynamics of the Jovian system.

But the primary mission of Ulysses will provide its most spectacular data. The Sun is a fabulously complex fusion reactor, where the energy produced in the core takes a million years to reach the surface of the star. The processes that make that possible are little understood.

The fusion process which produces the energy of the Sun and all of the stars is a process scientists have been trying to duplicate in Earth-bound laboratories since the 1950s. Their goal is to develop an inexhaustible source of energy for use on Earth. Studying the Sun from a new perspective will doubtless shed light on the process of nuclear fusion, the dynamic functioning of stars, the relationship between our star and the planets of the Solar System, and the history of the universe itself.

craft—it was too far along in design to be changed. About 80 scientists were eliminated from the project.

In June 1984, Dornier completed the spacecraft, and it was put into storage awaiting a Shuttle launch that had now been postponed to May 1986. In August 1984, ESA decided to rename the mission Ulysses. As ESA explained, in the 26th Canto of *Inferno,* Dante describes the last voyage of Ulysses beyond Gibraltar, a region at that time unknown and unexplored. According to legend, Ulysses' crew mutinied out of fear and he exhorted them to courage:

Brothers, said I, that have come valiantly
Through hundred thousand jeopardies undergone
To reach the West, you will not now deny

To this last little vigil left to run
Of feeling life, the new experience
Of the uninhabited world behind the Sun.

Think of your breed; for brutish ignorance
Your mettle was not made; you were made men
To follow after knowledge and excellence.

As the May 1986 launch of Ulysses drew near, the European Space Agency control team moved to the Jet Propulsion Laboratory in California, where the data from the Ulysses spacecraft would be received. The flight and ground safety reviews were completed, and the upper stage and support hardware were shipped to the Kennedy Space Center in Florida.

Four months before Ulysses was scheduled to be launched, the Space Shuttle orbiter Challenger and its crew were destroyed. The resulting two-and-a-half-year shutdown of the Shuttle program pushed the Ulysses mission to October of this year.

But now, it is finally on its way.