ULYSSES

by Edward J. Smith and Richard G. Marsden

Within the last two years, in 1994-95, a spacecraft called Ulysses transited the Sun's polar regions for the first time, This accomplishment is comparable to the reaching of the Earth's poles within this century which brought the exploration of the Earth's surface to its conclusion. As in the case of Earth, the Sun's polar caps were among the last regions to be explored. in the past, all spacecraft sent into interplanetary space have been restricted to the region near the Sun's equator which contains the orbits of the Earth and other planets. The reasons for this long wait and the means of overcoming it constitute an interesting episode in interplanetary navigation. More importantly, the scientific results being returned have. shown just how important it was to overcome the many obstacles met along the way.

From the first, the focus of the Ulysses mission has been on the Sun and its effect on our interstellar environment. When viewed from Earth by the naked eye or through a telescope, the Sun appears to be a bright, sharply-bounded disk. However, on those occasions when the Moon covers the Sun's disk to cause an eclipse, a diaphanous outer atmosphere called the solar corona can be seen extending into space. It was a surprise when, in the early 1950's, calculations showed that the corona actually reached out to, and past, the orbit of Earth. At about the same time, scientists realized that the gases trailing in the wake of comets in the form of a long tail pointed continuously away from the Sun because the corona was not only present but was flowing rapidly outward. The "solar wind" had been discovered. Further thought led to the conclusion that the many sun-like stars must commonly give rise to stellar winds of which the solar wind is but one example. in the interim, numerous spacecraft have left the region controlled by the Earth, the so-called magnetosphere, and entered the domain of the fast-flowing solar wind so that it could be sampled directly. The major goal of Ulysses has been to extend the knowledge accumulated by these earlier missions into the Sun's polar regions.

The existence of the solar wind has a profound effect on the interstellar medium in which the Sun and its planetary system are embedded. In the absence o f an extended corona flowing outward into space, the common constituents of interstellar space, consisting of gas, dust, magnetic fields, anti cosmic rays, would penetrate close to the Sun and fill the space between the planets. However, the solar wind, which carries a magnetic field along with it, clears the solar system of the bulk of interstellar material pushing it wc]] beyond the outermost planet, Pluto, to form a region dominated by the solar wind called the heliosphere. Of special importance to Ulysses is the effect of the solar wind on cosmic rays, atomic nuclei which have been accelerated to near the speed of light elsewhere in our Milky Way galaxy, In spite of opposition by the solar wind, an unknown fraction of the interstellar cosmic rays penetrate deeply into the heliosphere where, e.g., they bombard the Earth and have been under scientific observation and study for over a century. It was speculated that most of the cosmic rays in the solar system arrived by way of the Sun's polar regions, a possibility that a spacecraft might be sent to investigate.

The scientific justification for a mission like Ulysses which would escape the plane of the Earth's orbit about the Sun, called the. ecliptic, was recognized from the outset of the space age. 1 However, the means were not adequate to such an undertaking. To send spacecraft out of the ecliptic, it is necessary to overcome [lie rapid motion of the Earth, considered as a launch platform, about the Sun. Given this initial high velocity, even the most energetic rockets could not launch a spacecraft directl y into an orbit passing over the Sun's poles. It became evident that a flight path by a large planet, namely Jupiter, could be used to cancel this equatorial velocity component and propel the spacecraft into an orbit that was highly inclined to the ecliptic. After the two spacecraft, Pioneers 10 and 11, successfully flew by Jupiter in i 973-74 and demonstrated that solid-state technology could weather that planet's intense radiation belts, the way was open for the mission which was subsequently named Ulysses in honor of the classic Greek adventurer who also traveled to unexplored regions.

Although the mission was approved in 1977 as a joint venture of the US and European space agencies, the launch did not actually occur until October, 1990. The intervening years were occupied with the design, fabrication, and testing of the spacecraft and experiments as well as several major changes in launch vehicle and a series of political battles in the. United States to avoid cancellation of the mission. It had been the intent to make use of the NASA Shuttle supplemented by powerful secondary rockets, originally the liquid-fueled Centaur. However, a few months before the scheduled launch of Ulysses in 1986, the designated Shuttle, the Challenger, suffered a catastrophic failure, A delay in Shuttle launches of several years followed during which the Centaur was replaced by a safer three-stage solid rocket. A queue had developed involving planetary launches and Ulysses had to wait for Magellan and Galileo to be launched. These events account for the thirteen year delay between the approval of the ou(-of-ecliptic. mission and the actual launch of Ulysses.

The mission was put at risk, politically, shortly after having begun. in the first years of the Reagan administration, a decision was made, by NASA to cancel the US contribution to what had been agreed to as a two spacecraft mission, one spacecraft to be built by ESA and one to be built by NASA. The latter contained all the imaging investigations and one-half of the experiments provided by Europe. In the late 1970's, the House Appropriations Committee recommended complete cancellation of the mission. This threat was successfully overcome by judicious lobbying of Congress and the staunch support of the House Authorization Committee. Although cancellation of the US spacecraft caused much consternation in Europe and led to an unsuccessful appeal by the European Ambassadors to the US State Department, it was finally decided to proceed solely with the European-built spacecraft and with an experiment complement that was half European and half American. The collaboration then consisted of NASA launching and acquiring data from the. European spacecraft which was to be operated by European personnel using NASA facilities.

The medium inside the heliosphere being investigated by Ulysses is unusual as compared to our own atmosphere. Not only is the composition different, being approximately 90% hydrogen rather than oxygen and nitrogen, but the extremely high coronal temperature of approximately one million degrees insures that no neutral atoms are present. The corona and solar wind are electrically neutral but made up of equal numbers of ions and the electrons which have been removed from the neutral atoms to create the ions. Furthermore, the densities are so low that once ionization occurs, subsequent collisions are unlikely. in the absence of collisions, the ions and electrons are bound together by electric and magnetic fields. Such a medium is called an ionized, collisionless "plasma". As such, it represents a fourth state of matter, in addition to the usual gases, solids, and liquids, one which is thought to be found commonly throughout the universe in other hot, low density regions. The opportunity to investigate such a medium *in situ* is, in fact, a major motive in studying the heliosphere.

observations by in-ecliptic spacecraft have shown that the solar wind does not come from everywhere on the Sun but from regions associated with specific coronal structures. One of the most important structures takes the form of bright, often loop-like extensions of the corona that reach high altitudes in the vicinity of the solar equator especially near sunspot minimum. These structures, called streamers, are imposed by the global magnetic field of the Sun which, like. that of the Earth is generated by currents deep inside its fluid interior. It can extend well above. the surface and consists of loop-like lines of force that begin in one hemisphere and end in the other. Another dominant coronal structure appears at high latitudes near sunspot minimum and tends to cover the polar caps, It appears in images as an absence of coronal material and is, therefore, called a coronal hole. Holes are regions from which fast solar wind has come which accounts for the absence of brightness. Coronal holes are also a manifestation of the Sun's magnetic field which points outward in such regions without looping back to the opposite hemisphere. Such lines of force of the magnetic field, which have one end on the Sun and the other end carried off by the solar wind, are said to be "open" in contrast to the loop-like fields which are "closed".

The solar wind that comes from equatorial regions adjacent to the. streamers is slower than the wind from the polar corona] holes. Because the symmetry axis of the Sun's magnetic field is tilted relative to its rotation axis, the solar wind in the ecliptic alternately comes from the streamers and is slow and from the coronal holes and is fast. Before the slow wind has time to reach the orbit of Earth, it is overtaken by the following fast wind and is compressed and speeded-up. The fast wind is also compressed as a result of its collision with the preceding slow wine] and is slowed down. '1'bus, neither represent a sample of solar wind whose properties can be readily extrapolated back to their source regions on the Sun to understand the physical origin of the solar wind and possibly the heating of the corona.

The high temperatures associated with the. corona which account for its great extension into space have always been a puzzle. It is known that solar radiation alone cannot be responsible and that some alternative heat source must be involved. A favorite hypothesis is that the continual stirring of the Sun's visible surface, similar to a pot of porridge on a hot stove, generates mechanical rather than electromagnetic wave.s which propagate upward into the upper atmosphere where they deposit their energy. Another possibility, not inconsistent with the. former, is that intense small-scale magnetic fields located all over the Sun represent a source of stored energy which is sporadically converted into heat. It has long been supposed that, whatever process is responsible, it is imprinted on the solar wind and that by measurement and judicious interpretation of the solar wind properties its identity might be revealed.

Although the physical origin of the solar wind is thought to be understood in general terms, many details are still obscure. The presumed heating of the corona and solar wind, which may have a common origin, lead to a high pressure which tends to push the coronal plasma away from the Sun. This outward expansion is opposed by the Sun's strong gravity field. A competition between these two opposing forces is analogous to that which takes place in a rocket engine where hot gases generated in a combustion chamber (the hot corona) are allowed to expand through the restraint imposed by a nozzle (the gravity field). The essential feature of both is the conversion of heat into outward-directed fast flow. While such understanding is helpful, attempts to reproduce the observed solar wind properties using mathematical! models and assumed conditions in the corona have not been universal] y successful, Often, it has proven necessary to introduce additional unobserved features such as an "after burner" located wc]] above the visible corona.

Ulysses observations of the solar winds at high latitudes have answered two basic questions: 1s the solar wind from the polar regions free of disturbing interactions? To what extent dots solar wind from the polar caps reach down into the ecliptic? As Ulysses first left the ecliptic traveling southward, it passed into a region of continuous high-speed wind issuing from the south polar coronal hole. The speed of this high latitude wind was double that of the average speed of the low latitude, in-ecliptic wind, and was free of all but a few minor variations in speed. It is evident that, except for unusual conditions that depend on the solar cycle, the wind from the poles does not reach into the ecliptic. The fast winds that are typically seen in the. ecliptic come from the lower edge of the corona] holes and have a speed that is intermediate between the slow wind and the polar wind. However, the low latitude boundary of the wind was found to be significantly lower than the latitude corresponding to the edge of the coronal hole which was its source. This finding demonstrated that, although it did not reach down into the equatorial region sampled by the Earth, the volume occupied by the polar wind did expand by about a factor of five after leaving the Sun's polar cap. Evidentl y, close to the Sun, probably within perhaps five to ten solar radii, the solar wind flow departs from being strictly radial and is forced to acquire an equatorward component of motion.

The explanation of this non-radial expansion has also been provided by Ulysses. Magnetic measurements by the spacecraft over the full range of latitudes failed to show an increase in magnetic flux in the polar regions. indirect observations of the Sun's field from Earth, made by studying the splitting of spectral lines, have shown that the global field is similar to that of the Earth and to the common bar magnetic. The field is concentrated in the vicinity of two magnetic poles having opposite polarities, one located near the. north and the other near the south solar pole. Since the magnetic field is stronger at high latitudes near the Sun but is essentially the same at all latitudes at the location of Ulysses, it follows that the solar wind overexpansion mentioned above is being caused by magnetic forces. These forces push the solar wind toward the equator until an equilibrium condition is reached when the magnetic flux carried by the solar wind is uniformly or evenly distributed.

The measured magnetic flux at Ulysses combined with the expansion factor given by the solar wind measurements implies a field strength at the Sun's poles that is about ten time.s stronger than the Earth's field at the poles. The determination of the Sun's polar field strength by Ulysses is an important result because Earth-based observations of the Sun's polar fields are restricted to the line of sight and the strength of the polar magnetic fields, perpendicular to the line of sight, has traditionally been difficult to infer.

For many years, the electrically-charged cosmic rays have been known to be entering the solar system from the galaxy. They were originally identified by their continuous bombardment of the Earth and its atmosphere. The earliest spacecraft measurements of cosmic rays confirmed their extrasolar origin and extended the cosmic ray observations to even lower energies than those 'recorded at the Earth's surface. It is not easy, however, for galactic cosmic rays to penetrate into the inner heliosphere but, like Alaska salmon swimming upstream to spawn, they must overcome severe obstacles.

The low densities of the cosmic rays and the solar wind insure that collisions are absent and that the two kinds of particles do not interact directly. However, when the solar wind leaves the corona, it carries part of the solar magnetic field along with it, These are the "open" field lines mentioned above, The magnetic lines of force have tension and can be thought of as being stretched out into space like rubber bands. As the solar wind expands, the magnetic field continues to be reasonably strong, decreasing much less rapidly with distance than the Earth's field, for example, because electrical currents are established within the highly conducting solar wind plasma which sustain the field. The cosmic rays may be oblivious of the solar wind protons and electrons, but they are subject to one of the fundamental forces which magnetic fields exert on all moving electrically-charged particles, namely, the Lorentz force.

The principal effect of the magnetic force is to cause the cosmic rays to spiral around the magnetic field while simultaneously traveling along the field direction. Other characteristics of the magnetic field also play a role. The trajectories of the individual cosmic rays are influenced by a large-scale curvature or winding up of the magnetic field introduced by the slow rotation of the Sun. Variations in the field strength with distance also affect the cosmic rays. However, the major effect is associated with abrupt changes in the field direction. One cause of such changes are waves propagating along the magnetic field like the vibrations of a taut string or the wavy motion of a flag in a stiff wind. In effect, the cosmic rays are like a swimmer trying to enter the ocean in the presence of a strong surf. The fraction of the incident cosmic rays able to penetrate the heliosphere and reach the interior is unknown so that the intensity of cosmic rays in interstellar space is also uncertain.

Prior to Ulysses, it was speculated that cosmic rays would find it easier to enter the heliosphere over the Sun's poles then by way of the equatorial region. 'There were two principal reasons. First, the magnetic lines of force were expected to be straighter, or less tightly wound, over the poles than at the equator. 'This effect would result in a shorter path length for the cosmic rays arriving over the poles. Second, it was considered possible that there would be a relative absence of waves and other changes in field direction because of the smoother flow of the solar wind from the polar coronal holes.

However, when Ulysses reached high latitudes, the cosmic ray measurements showed that the intensity was similar to that at the equator. Ulysses' magnetic field measurements also provided the explanation. Very large amplitude waves were found to be continuously present with wavelengths, i.e., the distance from peak to peak or trough to trough, comparable to the turning radius of the cosmic rays as they spiraled about the magnetic field. This correspondence assured a strong interaction between the waves and the. cosmic ray particles that opposes their entry into the polar caps.

The observation of similar intensities at the *poles* and equator implies that all the cosmic rays reaching the inner heliosphere have been homogenized as efficiently as if they were part of a milkshake. Stated another way, the cosmic rays have traveled a long path from the edge of the heliosphere, have undergone many "collisions" with magnetic field irregularities, and have lost all knowledge of where they entered the heliosphere or what their properties were when outside it in interstellar space. For cosmic ray physicists, the Ulysses results are a major step forward.

The highest energy particles inside the. heliosphere are the galactic cosmic rays (GCR). They are nuclei of atoms from which all electrons have been removed and which have been accelerated elsewhere in the galaxy to nearly the speed of light. There are other lower energy particles that originate inside the heliosphere. Their relatively high speeds distinguish them from the solar wind particles, Three separate components have been identified. Some particles are energized or accelerated at the Sun, The second distinct class of particles are accelerated within the. heliosphere after leaving the Sun. The third component consists of particles that enter the heliosphere as electrically neutral interstellar atoms which are accelerated after having become ionized. in general, of these three types, the particles accelerated in the solar wind have the lowest energies. The particles coming directly from the Sun have intermediate energies. The accelerated interstellar particles have the highest energies anti because they were originally confused with low energy cosmic rays are called anomalous cosmic rays (ACR).

The means by which charged particles gain high energies has long been a subject of scientific research. All such particles are called superthermal because they could not gain their high energies as a result of heating. Because collisions arc infrequent in solar anti astrophysical] plasmas, particles can gain large amounts of energy by being exposed to electric and magnetic fields. One possibility is that the acceleration process is similar to that which occurs in laboratory accelerators, called cyclotrons, or, in previous times, "atom smashers". Basically, the particles arc injected into these devices at low energy, are kept trapped inside the machine by a strong magnetic field about which they spiral and gain energy from a time-varying electric field.

Of course., nature typically operates differently from man-made machines whose design consists of several distinct parts. Nevertheless, the energetic particles in space are found in the vicinity of distinct magnetic anti electric field topologies or configurations. Some occur where magnetic fields having opposite directions arc brought into contact. By a poorly understood process, the energy inherent in the magnetic fields is annihilated anti given up to the particles that arc present. Energetic particles are also often found in the vicinity of large amplitude waves of the kind discussed above. in connection with their effect on galactic cosmic rays. Finally, a very fast-moving wave, corresponding on Earth to a "sonic boom" accompanying jet aircraft or the Space Shuttle when it re-enters the Earth's atmosphere, is often found to accelerate heliospheric particles.

The solar energetic particles are apparently produced at low altitudes where smaller scale intense magnetic fields abound ant] opposing field directions are common. The composition of these particles attests to their low altitude origin. At the temperatures and densities typical of the low corona the more easily ionized metals and certain other elements are typically favored. This region is likely to bc one in which magnetic field annihilation is occurring.

In March, 1991, Ulysses, then en route to Jupiter, observed the effect of a whole series of large outbursts of solar energetic particles that continued for an interval of about a month. During this long period, the inner heliosphere was continually filled with a superposition of particles from these several distinct events whose intensity decayed slowly over a period of about one month. The observations showed that the solar wind magnetic fields were capable of trapping these. particles throughout a huge volume from which they could only escape slowly.

Strong, time-varying electric and magnetic fields occur as part of the interaction between fast and slow solar wind. A curved front of high pressure is formed which gives rise to large amplitude waves propagating away from the front in both directions, i.e., forward into the slow wind and backward into the fast wind. These waves gradually steepen, like ocean waves approaching a beach, anti by the time they reach a distance about twice the distance from the. Sun to Earth, they have developed into shock waves corresponding to the sonic booms mentioned above. Shock waves travel at speeds faster than the speed of "sound". In the solar wind, sound waves arc replaced by the types of waves that can propagate in collisionless plasmas, for example, as a kink in the magnetic lines of force. Shocks arc also thin surfaces across which all the solar wind properties change abruptly and, in particular, they nvolve large jumps in electric and magnetic fields.

observations by spacecraft prior to Ulysses demonstrated that the broad disordered interaction regions and the shocks are the site of energetic particle acceleration. These energetic particles tend to appear with clock-like regularity, typically twice each solar rotation, as solar wind from near the equator alternates with fast wind from first one and then the other polar cap. Numerous instances of energetic particles accompanying these complexes were observed by Ulysses while it was en route to Jupiter and, afterward, throughout the equatorial region. As the spacecraft left low latitudes and reached the region of fast wind from the polar caps, the interaction regions and the shocks disappeared because the steady flow of the fast wind precluded the piling up of plasma to form fronts. It was, therefore, surprising to find that, although these solar wind structures were absent at the spacecraft, the clock-like appearance of energetic particles continued to very high latitudes.

Three hypotheses have been advanced to explain how energetic particles can reach high latitudes. The waves accompanying the fast wind (mentioned above as responsible for keeping out the cosmic rays) may allow the! particles to transfer from low latitude to higher latitude magnetic field lines. This process is analogous to diffusion, an example of which is the way in which smoke from a cigarette will slowly fill a room. Second, the shocks may reach higher latitudes further out in the heliosphere and the energetic particles may the.n follow magnetic lines of force back toward the Sun at higher latitudes. '1'bird, field lines at high latitudes may be brought down near the equatorial interaction regions at larger distances. Scientists arc continuing to analyze these measurements and to develop and test mathematical models in an effort to resolve this mystery.

Anomalous cosmic rays (ACR) have an unusual history. They originate as atoms of neutral interstellar gas that are continually entering the heliosphere because of their motion relative to the Sun. Because atoms are electrically neutral, they are unaffected by the magnetic fields inside the heliosphere. However, those atoms whose trajectories take them close to the Sun become ionized as one of their outer shell electrons is removed either by short wavelength solar radiation (the same radiation that sustains the Earth's ionosphere) or by infrequent collisions with solar wind ions (because the neutral particles move so slowly compared to the solar wind and the heliosphere is so vast, they spend a long time in the solar wind and, eventually, such a collision can occur). once an interstellar ion is created, it senses the solar wind magnetic field, is "picked up" by it and joins the general flow away from the Sun.

Ulysses has, for the first time, identified many different types of pick up ions, namely, H^+, He^+, He^{++}, C^+, N^+, and O^+. These observations and the improved understanding of their evolution inside the heliosphere are expected to yield an accurate determination of the abundances of these atoms in interstellar space, information of keen interest to astrophysicists.

In the coordinate frame of the rapidly-moving solar wind, the interstellar pick up ions appear to spiral rapidly around the magnetic field or, in equivalent terms, to be hot compared to the solar wind ions. These hot wind ions have been found to coexist with the solar wind ions as a distinct component. Prior to Ulysses, it had been supposed that the two ion populations, in spite Of their very different origins, would meld into a single plasma, but measurements show that this is not happening or else is taking place very slowly. The ultimate fate of a substantial number of the interstellar ions is that they are accelerated to near cosmic ray energies. Obviously, the processes involved are, of great interest since particle acceleration seems to be a widespread phenomenon throughout the universe and is not well understood at present. The acceleration appears to be taking place in two stages. First, the shock waves propagating through the heliosphere have been shown by Ulysses to be very efficient at accelerating the interstellar ions to intermediate energies. Presumably, efficiency is high because the interstellar ions are hot before they encounter the shocks and their accompanying field irregularities. Each such shock wave can successively raise the energy to higher and higher values.

Prior to the Ulysses observations, acceleration of interstellar ions was thought to occur at another type of shock wave that is part of the internal structure of the heliosphere. Before the solar wind reaches the boundary with the interstellar plasma and magnetic field, it has to be slowed-down and deflected from a radial flow so that it can slide along parallel to the boundary and out of the heliosphere through a long open "tail". Theorists have favored an abrupt, rather than a gradual, change from the fast radial flow characteristic of the solar wind as we know it. They have speculated that the solar system is enclosed in a spherical shock wave inside the heliosphere at perhaps one hundred times the Sun-Earth distance. This structure is called the termination shock (because it terminates the characteristic solar wind flow). It is expected to be "standing" or have its location fixed relative to the Sun because it is propagating Sunward at the same speed as the outward flowing solar wind and the two speeds cancel in the Sun's frame of reference.

The termination shock has played a key role in our ideas about the acceleration of the interstellar ions ant] the formation of Anomalous Cosmic Rays. Before Ulysses demonstrated that acceleration was taking place at traveling shocks well inside the termination shock, it was assumed that ACR were accelerated only by the latter. in that context, theories were developed that emphasized the potentially unique character of the termination shock above the Sun's poles. Because of the radial field orientation that was commonly assumed, which ignored the non-radial solar wind expansion uncovered by Ulysses, the shock structure was considered to be especially favorable for particle acceleration. Another possibility which received attention was the shorter path available to the particles along polar field lines and the possible absence of opposition by waves propagating along the field. These considerations parallel those described above in connection with GCR. The prediction of such models was a large increase in the flux of anomalous cosmic rays at high latitudes.

As with the galactic cosmic rays, this possibility was shown by Ulysses to be untenable. The Ulysses energetic particle experiments were able to distinguish and study ACR over a wide range of energies and elements (C, O, etc.). They revealed only a gradual increase in A(R intensity with latitude. The main reason, as with the GCR, is the continuous presence of large amplitude waves throughout the polar regions which oppose easy entry of the particles into the polar caps.

This discussion of energetic particles concludes our summary of some of the principal scientific results obtained by Ulysses. The spacecraft is now following its elliptical orbit outward toward the orbit of Jupiter where it will arrive in April, 1998. Jupiter will be located elsewhere and will be far from the spacecraft at that time. Nor will Jupiter influence the Ulysses trajectory over the next several hundred years. '1'bus, the spacecraft will continue to travel along its present highly inclined ellipse. for the. foreseeable. future.

1 'ortunately, the spacecraft and the experiments are continuing to operate without fault and NASA and ESA have agreed to continue acquiring data during the second orbit around the Sun. Continued observations arc very desirable scientifically because all the phenomena described above are. strongly influenced by the eleven year solar cycle, the most obvious manifestation of which is the sunspot cycle. By good fortune, the period of the. Ulysses orbit is approximately six years or one-half of the sunspot cycle. Ulysses was over the Sun's poles in 1994 and 1995 when the Sun was in its quiescent phase and transient solar activity, which causes aurora and magnetic storms on Earth, was minimal. The polar caps have been seen when conditions were at their simplest, When Ulysses passes over the Sun's poles again in 2000 and 2001, it will be sunspot maximum and all of the above phenomena will be changed

drastically. Ulysses scientists are looking forward eagerly to this event while continuing to make observations in the meantime. Although much has been learned, a great deal remains to be studied and discovered as the odyssey continues.