Ulysses

A VOYAGE ABOVE THE SUN'S POLES

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First results highlight the Ulysses spacecraft's potential to report on physical conditions and processes of which we have no direct knowledge in previously unexplored territory above the Sun's polar caps. Launched in October 1990, we anticipate Ulysses will provide detailed information about the Sun, the heliosphere, the local interstellar medium, and about signals invading the solar system from distant parts of our Galaxy.

Ulysses is unique because although Earth satellites are commonly injected into either polar or equatorial orbits, previous interplanetary missions have been restricted to the vicinity of the Sun's equator. Spacecraft are launched from a moving platform, namely the Earth, which is travelling around the Sun in the ecliptic plane at a speed of 30 km/s. No combination of available launch vehicles can simply add a large enough velocity component perpendicular to the ecliptic to pass directly into a high inclination. Ulysses will instead achieve an inclination in excess of 80° by moving outward to Jupiter and using a gravity-assist to "crank" the orbit plane. The spacecraft, reaching Jupiter in February 1992, will end up in a large elliptical orbit about the Sun and spend 235 days above 70° heliographic latitude (both North and South), equivalent to about eight solar rotations. The trajectory is represented in Fig. 1 along with the dates of important milestones.

The scientific capabilities of Ulysses have been strongly influenced by knowledge gleaned from in-ecliptic missions. The spacecraft (see page 205) carries nine instruments to make comprehensive, quantitative measurements of the particles and fields along its orbit. For most of the investigations, observations in the polar regions of the heliosphere are either advantageous or crucial.

We review here the objectives behind the experiments and the excellent potential for new discoveries revealed by results obtained during the first few months on the outbound leg to Jupiter.

The Sun and Solar Wind

The principal focus of the mission is the Sun, especially its outer atmosphere, the corona. A striking feature of the visible corona is that it extends to several solar radii, indicative of temperatures above 10^6 K. The kinetic energy of the constituent particles is large enough that portions of the corona flow outward to form the solar wind.

Neither the heating of the corona nor its acceleration to form the solar wind are well understood. The availability of coronal samples in the form of the solar wind has encouraged a search for an imprint of the physical processes heating the corona. In spite of the many observations near the solar equator, it has proven difficult to reconcile the observed properties of the solar wind with known conditions in the corona, or to identify the heat source.

Observations by Ulysses in the polar regions to address these two, closely related, problems in solar (and stellar) physics have important advantages: the solar wind presumably originates from the centres of the large coronal holes (regions where few X-rays are emitted) covering the polar caps. There should be an absence of solar-rotation phenomena, freeing the measurements from the complicating effects of the longitude dependence characteristic of in-ecliptic observations, to allow extrapolation of solar wind conditions back to the corona with improved accuracy.

Second, coronal magnetic fields extending upward from their sources below the visible surface (photosphere) are intimately related to the solar wind: they can obstruct the outward motion of the plasma and interrupt the solar wind flow where the field is strong and transverse to the radial direction. In regions where the field tends to be more radial, the solar wind can form and, because of its large electrical conductivity, carry ends of the magnetic field force lines into space. This field-plasma interaction has two important consequences: the solar wind originates from specific coronal regions, not from the entire corona, and it is magnetised.

Although the main part of Ulysses voyage — the out-of-ecliptic path — still lies ahead, the initial data obtained during the first few months of the mission clearly demonstrate the potential of solar wind instrumentation to make new discoveries. Ulysses carries the solar wind ion composition spectrometer (SWICS), the first continuous ion mass spectrometer to operate successfully and with an exceedingly low background in interplanetary space. Unlike earlier instruments, SWICS determines both the mass and charge state of ions over an extended energy range from 0.65 to 60 keV/e using electrostatic analysis and post acceleration, time-of-flight

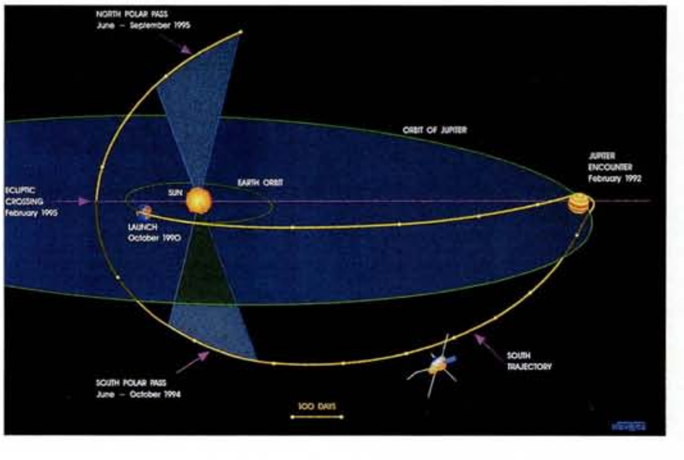

Fig. 1 — Ulysses' trajectory viewed from 15° above the ecliptic plane. The heliographic latitude exceeds 70° above the Sun's poles in the shaded areas.

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and energy measurements. A typical distribution of the observed mass per charge of selected ions in the solar wind (Fig. 2) shows that the three charge states of carbon are well resolved and separated from O^{6+}.

The highest resolution is obtained by plotting the individual event data from SWICS in the form of a mass *versus* mass per charge matrix (cover illustration). A large number of elements and their charge states are readily resolved. Clear separations, especially of ambiguous ions such as He^{2+} and C^{8+}, allow the abundances of many minor ions to be determined for the first time.

New information on temperatures and temperature profiles in the solar corona, the birth place of the solar wind, will be obtained from this and similar data. Initial results indicate, for instance, that O ions rather than C and Fe ions tend to originate in hotter regions of the corona.

Non-solar contributions

It has been proposed that cometary and asteroidal material, gradually evaporating and becoming ionised on approaching the Sun, may contribute to the ions observed in the interplanetary medium. Ions produced this way should have a broad distribution of charge states, reaching down to charges much below those of the proper solar wind ions. Fig. 3 shows that ions with low charges, *e.g.*, Cl^{+}, O^{+}, Si^{2+}, Fe^{3+}, Fe^{4+}, Fe^{5+}, are, however, much rarer in the solar wind than the corresponding ions with high charges. This low abundance places a severe upper limit on any non-solar contributions to these ions. The ion abundances observed on Ulysses in fact agree well with charge state distributions predicted by model calculations based on ions originating in the solar corona.

Polar magnetic fields

In the absence of solar rotation, the magnetic field in the solar wind would extend radially outward. However, as the sun is rotating, the field lines are only radial in the polar regions, while at lower latitudes extending down to the equator they are wound-up to form helices or spirals. This basic asymmetry in the magnetic field is a major reason for expecting conditions to be different and simpler in the polar regions than near the equator.

The solar magnetic field in the polar caps — clearly an important component of the Sun's field — is poorly observed from Earth. So a major objective is to determine accurately the field strengths in the polar caps by measuring polar fields and extrapolating them back to the Sun.

Solar flares

Another major solar objective of Ulysses is the investigation of various physical processes associated with solar flares. Flares are unpredictable short-lived outbursts which release vast amounts of energy in a variety of forms: radiation, extending from gamma- and X-rays to radio waves, and energetic particles including both ions and electrons. X-ray investigations use the Sun as an occluding disc to study the altitude distribution of the source regions; radio waves from flares are detected as they propagate through the outer corona and the solar wind.

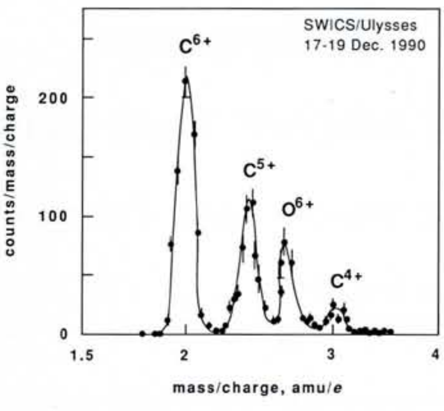


Fig. 2 — Examples of well-resolved mass per ionic charge distributions of selected solar wind ions as measured by the solar wind ion composition spectrometer (SWICS) on Ulysses (courtesy of Bern Univ., Switzerland, and Maryland Univ., USA).

The behaviour of the charged particles associated with flares is extremely complex. The mechanism which accelerates the particles to high energies is uncertain. Numerous possibilities have been suggested, many involving the conversion of magnetic into kinetic energy. After acceleration, particles can be stored for a time in strong coronal magnetic fields before finding their way onto field lines which open outward into the solar wind. The particles can then stream away from the Sun at high speed, although their motion can be strongly influenced by waves and other irregularities in the solar wind magnetic field which act as scattering centres. Observations of solar energetic particles made while Ulysses ascends from the equator to the poles should provide a valuable new perspective on these processes, and help distinguish the changes which the particles undergo.

The Solar Wind and the Heliosphere

The solar wind exerts an outward pressure on the interstellar plasma and magnetic field surrounding the solar system, thereby creating the heliosphere, a large volume in interstellar space inside which solar matter and fields are dominant. The evolution of the solar wind and the global structure inside the heliosphere are of current scientific interest and are being studied by the Pioneer and Voyager missions at large heliocentric distances.

Ulysses will provide the first observations of the polar heliosphere. The evolution of the solar wind velocity, density, temperature and composition will be studied and the presence and properties of various wave species — important components of the internal dynamics — will be assessed. Of special interest is the extent to which the solar wind from the polar caps diverges to eventually reach the ecliptic and influence the properties of the solar wind observed there.

Energetic particles

The heliosphere is populated by high energy particles that have been accelerated at various locations. In addition to the solar flare particles, ions and electrons are raised to high energies by interacting with large scale structures in the solar wind. A ridge of high pressure develops as a fast moving solar wind overtakes a slower moving wind from a source at a different longitude. The edges of this ridge tend to steepen into collisionless hydromagnetic shocks. Shocks are also caused by solar flares which are often accompanied by the emission of rapidly moving clouds of plasma (so-called coronal mass ejections). The acceleration of particles by shocks travelling near the solar equatorial plane is well documented, but do such shocks occur at higher solar latitudes and are particles accelerated by the same or other means? Ulysses will address these important questions.

Anomalous cosmic rays

Another heliospheric constituent of special interest is the anomalous cosmic ray component, namely particles occupying the energy range between the solar-heliospheric particles and galactic cosmic rays. They enter the heliosphere as neutral atoms of interstellar gas, principally elements with high ionisation potentials such as He, C, N, O and Ne, are ionised and then accelerated, probably at a shock wave that forms inside the heliosphere at large distances. Once accelerated, the anoma-

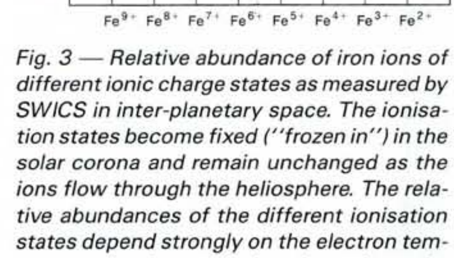


Fig. 3 — Relative abundance of iron ions of different ionic charge states as measured by SWICS in inter-planetary space. The ionisation states become fixed ("frozen in") in the solar corona and remain unchanged as the ions flow through the heliosphere. The relative abundances of the different ionisation states depend strongly on the electron temperature in the coronal region where the freezing-in occurs (courtesy of Bern Univ., Switzerland).

lous cosmic rays are energetic enough to return to the inner heliosphere, where they are observed.

Ulysses' observations will provide a rare opportunity to re-examine their origin and propagation in a drastically different regimes which may arise owing to differences between heliospheric shocks formed in the radial polar and the transverse equatorial magnetic fields. Second, owing to shorter, less irregular magnetic field lines in the polar region there should be a stronger connection between the point of observation and the acceleration region than for equatorial measurements.

Cosmic dust

The heliosphere also contains very small dust particles having an estimated lifetime of only 10^4 years, determined by gravitational and electromagnetic forces, implying that they must be continually replenished. Both the sources of the particles, thought to be asteroids, comets and the interstellar medium, and their dynamics are debated. Observations by Ulysses over a broad range of latitudes should reveal much about the distribution and evolution of the dust.

The Interstellar Medium

Interstellar wind

The interface between the solar and interstellar magnetised plasmas is not an effective barrier to other interstellar constituents. Neutral gases, principally hydrogen and helium, can readily penetrate into the heliosphere where they interact with the Sun's gravitational and radiation fields. Helium represents an interesting contrast to the more plentiful hydrogen: it is much less readily ionised and its additional mass means that the solar gravity dominates the radiation pressure in determining the trajectories of the atoms as they pass through the solar system. The direct detection of helium atoms, attempted for the first time on Ulysses, will yield an accurate determination outside the heliosphere of their bulk velocity, density and temperature in this "interstellar wind". First results for the velocity and arrival direction are in line with earlier remote sensing data in that the helium and hydrogen wind streams are flowing together, but at slightly different speeds.

Galactic radiation

The constituent of the interstellar medium set to receive the most attention is galactic radiation. Cosmic rays originate in the Galaxy, presumably as a result of supernova explosions, and form a gas consisting of relativistic charged particles. On the scale of the heliosphere, they act like individual particles whose large gyroradii about the weak magnetic fields in the vicinity of the heliopause allow them to enter the heliosphere. Once inside, the cosmic rays sense the solar wind magnetic field and are guided as they attempt to travel further inward. However, magnetic field irregularities — a characteristic feature of the supersonic, turbulent solar wind — tend to scatter the cosmic rays which must then essentially diffuse into the inner heliosphere rather than simply propagate inward along helical field lines.

The motion of the magnetic field as it is carried outward by the solar wind, as well as the large scale global properties of the average field, also influence the evolution of the cosmic rays. As a result of these combined effects, rays eventually reaching the inner solar system have their properties altered so drastically that properties outside the heliosphere are unknown.

A major objective of Ulysses is to determine the intensity, energy spectra, composition and other properties of galactic cosmic rays in the Sun's polar regions. The anticipated tendency for much shorter field lines in the nearly radial polar magnetic field than in the tightly spiraled in-ecliptic fields is one reason for expecting that cosmic rays will have easier access to the heliosphere over the poles so their properties there may be modified much less than in the ecliptic. Ulysses may finally make it possible to determine the properties of the primary galactic cosmic rays — a long-cherished goal of cosmic ray research.

Signals from the Galaxy

Gamma ray bursts

The origin of gamma-ray bursts — short bursts of gamma rays of short duration and millisecond time variation — known for over 15 years, is still mysterious. Their simultaneous detection over the long baseline formed by Ulysses and Earth-orbiting spacecraft such as the Gamma Ray Observatory launched in 1990, will pinpoint their astrophysical sources. Six bursts have already been identified by Ulysses in conjunction with other spacecraft.

Gravitational waves

According to the general theory of relativity, a spatial strain propagating at the speed of light causes a minuscule change in the distance between two bodies such as a tracking station and a spacecraft. Evidence for these gravitational waves, as yet undetected in spite of determined international efforts, will be sought. Their detection would enable the study of massive objects and their motions, including those which presumably occur during the creation or interaction of black holes.

A Doppler signal will be introduced at an Earth-borne station that is simultaneously receiving and transmitting as the supposed gravitational wave sweeps over it and subsequently the spacecraft: evidence would be detected as a characteristic sequence of three pulses.

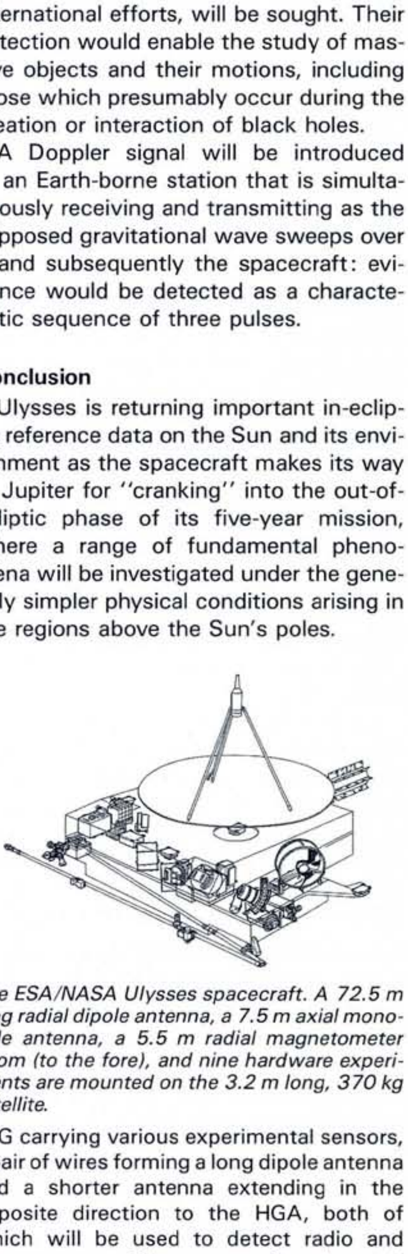
Conclusion

Ulysses is returning important in-ecliptic reference data on the Sun and its environment as the spacecraft makes its way to Jupiter for "cranking" into the out-of-ecliptic phase of its five-year mission, where a range of fundamental phenomena will be investigated under the generally simpler physical conditions arising in the regions above the Sun's poles.

The ULYSSES Spacecraft

The Ulysses adventure represents a partnership between the European Space Agency (ESA), the US National Aeronautics and Space Administration (NASA), and scientists on both sides of the Atlantic. But the solar-heliospheric research community waited a long time. The mission was first discussed in 1959 at the dawn of the Space Age, but was only approved in 1977/8 and launched last 1990. It aims to determine: the composition of the ionised interplanetary gas, the solar wind and its velocity, density and temperature; magnetic fields and the various species of waves, from those with the longest periods to high frequency radio waves; energetic particles of solar origin, as well as galactic cosmic rays, together with neutral helium atoms originating in interstellar space and cosmic dust. There is remote sensing of solar X-rays, extra-solar gamma-ray bursts, and possibly gravitational radiation.

The spacecraft consists of a main body on which a fixed, high gain antenna (HGA) is mounted (see figure). Various appendages protrude outward: a Radioisotope Thermoelectric Generator (RTG) power source, a 5.5 m boom deployed opposite the RTG carrying various experimental sensors, a pair of wires forming a long dipole antenna and a shorter antenna extending in the opposite direction to the HGA, both of which will be used to detect radio and plasma waves. The spacecraft spins at 5 rpm to provide stabilisation, data averaging and antenna extension. An on-board tape recorder stores scientific data for continuous measurements while requiring only a single playback per day to a ground station antenna. ESA is responsible for on- and off-line data processing and distribution: all experiments are functioning normally.



The ESA/NASA Ulysses spacecraft. A 72.5 m long radial dipole antenna, a 7.5 m axial monopole antenna, a 5.5 m radial magnetometer boom (to the fore), and nine hardware experiments are mounted on the 3.2 m long, 370 kg satellite.