On 6 October 1990, the Ulysses spacecraft was launched to begin the exploration of the heliosphere in three dimensions, that vast region of space carved out by the influence of the Sun. A European Space Agency (ESA) spacecraft, launched and tracked by NASA, with instruments provided by both Europe and the United States, Ulysses is a classic example of international cooperation. Like all classic examples, however, Ulysses provides lessons on what to do and what not to do. (The Ulysses mission has had many names, from the Out-of-the-Ecliptic Mission to the International Solar Polar Mission to its current name, Ulysses, which was given to it in 1984. The mission has been the same, but the name has changed, and so for simplicity in this article, we will use the name Ulysses throughout.)
Ulysses has been a long saga, dating from the early 1970s and continuing even today. It had its initial trials and, like all good stories, it ends in triumph. I will relate that story here, for the lessons it provides. The Ulysses story is also intertwined with the ISSI story. There are common participants who shaped ISSI in part by their Ulysses experience. And ISSI has been the venue where the triumphs of Ulysses have been exhibited.

We begin by discussing why the exploration of the heliosphere was considered to be important, and how the current Ulysses mission evolved. We then review some of the discoveries made that reserve for Ulysses a place in history. Our story will end with ISSI; the threads that developed in Ulysses evolve into ISSI, and at ISSI the discoveries of Ulysses are honed into understanding.

The Beginning

It is a simple fact of orbital dynamics that when you launch a spacecraft from Earth into the Solar System, the main velocity vector lies in the plane of the Earth’s orbit, and thus it is confined to lie near the equatorial plane of the Sun. Prior to Ulysses, then, all spacecraft that were launched to explore the region of space influenced by the Sun were confined to a relatively narrow plane in an otherwise vast three-dimensional region. Indeed, prior to Ulysses, we referred to our region of exploration as the interplanetary medium, or interplanetary space, in recognition that it was the region between the planets, whose orbits all lie near this single plane. Ulysses, as we will discuss, has explored the full three-dimensional heliosphere, and created true heliospheric science.

The deficiencies of our exploration were well recognized early in the space program. There was no expectation that the interplanetary medium that we were able to explore was representative of the broader heliosphere. Our sampling was certainly biased. The outer atmosphere of the Sun continually expands into space to form the solar wind. The fastest solar wind originates from so-called “coronal holes” on the Sun, where the magnetic field is open, giving easy escape to the solar wind and resulting in low densities in the solar corona that appear dark in X-rays (hence the name coronal holes). Coronal holes are very pronounced at the poles of the Sun during periods of low solar activity – solar-minimum conditions. There was an expectation, then unproven, that the solar wind would exhibit pronounced variations with solar latitude.

The expected configuration of the magnetic field in the solar wind results from the wind’s outward expansion, which drags the field radially outward, and from the assumption that the field remains attached to the rotating Sun. A spiral pat-
tern for the field will result. At our location at Earth, near the solar equatorial plane, the spiral pattern is relatively tightly wound. But over the solar poles, the magnetic field should be essentially radial, which presents much different conditions for the inward access of cosmic rays from the Galaxy. Indeed, during certain periods of the solar cycle, we might expect that cosmic rays would have easy access over the solar poles; in particular, lower-energy galactic cosmic rays, which are otherwise excluded, should be present in the inner heliosphere.

Perhaps the most significant aspect of our pre-Ulysses ignorance of the three-dimensional heliosphere was our lack of knowledge of how the magnetic field of the Sun reverses polarity during the solar cycle. The Sun has a 22-year magnetic cycle; the average dipolar field of the Sun reverses polarity every 11 years, with the reversal occurring shortly after the period of maximum solar activity. The polarity change is manifested in the magnetic field in the solar wind, which also reverses polarity. The question is how does this physically occur. Is old magnetic flux shed and new magnetic flux emitted; is there a time when the magnetic field in the solar wind has mixed polarity, and on what scale? Interestingly enough, this was not a question that was really asked or speculated upon prior to the launch of Ulysses, nor was it an anticipated discovery. Perhaps it was the uncertainty of when Ulysses would perform its exploration, and for how long. If the time period around solar maximum was not included, the subject of the field reversal might not be addressed. As we shall see, however, understanding the field reversal of the Sun has been one of the seminal discoveries of Ulysses.

In the late 1960s and early 1970s, the clamour for a mission that would explore the three-dimensional heliosphere began to build. Fortunately, it began to build on both sides of the Atlantic, with two principal advocates, Harry Elliot of Imperial College in Europe, and John Simpson from the University of Chicago in America. There was thus an opportunity for a joint US/European mission. In 1974, a delegation of US scientists and NASA planners journeyed to ESTEC in Noordwijk, The Netherlands, to discuss the possibility of a joint mission. To fly over the poles of the Sun, you must first go to Jupiter and use its gravitational field to redirect the trajectory of the spacecraft into the polar direction, as is illustrated in Figure 2. The question, then, was how best to do this as a cooperative mission. In a productive session at that joint meeting in 1974, Ian Axford, then Director of the Max Planck Institute at Lindau, Germany, went to the blackboard and drew what was to become the mission design: two spacecraft, one provided by ESA and one by NASA, both launched together towards Jupiter. Their trajectories split at this point, with one spacecraft heading over the south pole of the Sun, and the other heading towards the north pole. It was to be an ideal science mission, with the conditions over each pole observed simultaneously, and temporal and spatial effects readily separable. It was also to be an ideal interna-
tional cooperation: clean interfaces, with separate spacecraft, so that each side could readily perform its tasks without being overly dependent upon the other (a situation that proved to be both a blessing and a curse).

ESA and NASA have separate and different approval processes for new missions. And so, with a mission design in hand, each side went back to begin their separate, arduous processes of approval. In the US, a new mission must be first sold to NASA and the Executive branch of Government for a so-called "new start", and then sold to Congress for funding approval. NASA responds to community pressure, and so a workshop was held in May of 1975 at the Goddard Space Flight Center (close to NASA Headquarters) to demonstrate community interest and excitement in the study of the three-dimensional heliosphere. Even with such community encouragement, there was bound to be stiff competition for new starts among the various science disciplines that NASA supports. Indeed, the general field of solar and heliospheric physics had previously suffered in this competition because it was not well represented at NASA Headquarters. Fortunately, shortly before the new-start discussions, NASA had reorganized to form a Solar-Terrestrial Division, on equal standing with the more powerful division that pursued planetary exploration, and these circumstances made it possible to obtain a new start for Ulysses. New starts must then be approved by Congress, and after much encouragement from the science community, the new start for Ulysses was obtained in 1978.

Figure 2. The trajectory of Ulysses, first to Jupiter to use its gravitational field to redirect the trajectory to fly over the poles of the Sun.
Exploration of the Heliosphere in Three Dimensions with Ulysses

ESA has a different process from NASA, but with similarities. The issue is not persuading a Parliament, as with the US Congress, to approve Ulysses, but rather scientific representatives of the various Member States of ESA must be convinced. Herein lay the similarity. Someone had to be convinced that Ulysses was more worthy than competing projects, and the job fell to the science advocates of Ulysses. There were many acknowledged and unsung heroes in this effort, on both sides of the Atlantic, but since this is a story that weaves its way to ISSI, the role of Johannes Geiss should be acknowledged. As chair or member of various committees of the European Space Research Organisation (ESRO) and of ESA, Johannes Geiss was involved in many of the early discussions about an out-of-ecliptic mission. He became convinced of the importance of this exploration when the plans included flying to high heliospheric latitudes, and then as chair of the Solar System Working Group he defended the project energetically and with skill.

With the new starts well underway in Europe and the US, it was time to select the payloads. NASA, being ever more ambitious, was to fly a coronograph that would look downward from above the solar poles on the full corona of the Sun that flows outward and affects Earth. The payload on the ESA spacecraft was to be a full range of particle and magnetic-field experiments (see, for instance, the results in the volume edited by A. Balogh, R.G. Marsden & E.J. Smith). This being a joint European/US mission the scientific community on both sides of the Atlantic distributed themselves so that almost every experiment was an international collaboration. The selection then resulted in instruments on the ESA spacecraft with a strong US role, and instruments on the US spacecraft with a strong European role. One interesting difference, however, was that the Europeans were prepared to take more risks than the Americans. The Solar Wind Ion Composition Spectrometer, known as SWICS, was a US-European collaboration between the University of Maryland, with George Gloeckler as Principal Investigator, and major hardware contributions from the Max Planck Institute at Lindau, Germany, the University of Braunschweig, Germany, and the University of Bern, Switzerland, with Johannes Geiss in the lead. SWICS depended on an innovative design that involved the highest voltages ever to be flown in space, up to 30,000 volts. NASA was less comfortable with what they perceived to be the risk of SWICS, but the Europeans were more willing to accept it, perhaps because they delegate to the experimenters, and their national support, the responsibility for scientific instruments.

The unique orbit of Ulysses had to be matched by unique, advanced, and even entirely new scientific instruments. That was the opinion of Johannes Geiss and the Solar System Working Group, because – looking at the very limited resources of ESA’s Science Programme – they did not believe a second mission
for high-latitude exploration would be likely. Thus, not only was SWICS accept-
ed, but an experiment of the Max-Planck-Institute in Heidelberg was included as well. This instrument discovered interstellar grains deep inside the heliosphere. A most modern cosmic-ray experiment built by an American-European team headed by John Simpson was also among the experiments accepted for the European spacecraft. (They all have been operating successfully on Ulysses.)

In the late 1970s, then, all was well, with an exciting mission design and an excellent payload. Then disaster struck. Reagan was elected President of the United States in 1980, and as one of his first acts in office he slashed the NASA budget, and NASA unilaterally, and without consultation with ESA, cancelled the US spacecraft for Ulysses, and with it the opportunity to fly the internation-
al instruments it was to carry. NASA did continue to support its contribution to the instruments on the ESA spacecraft, and was to provide the launch and track-
ing. Those US experimenters on the ESA spacecraft were fortunate. Those European experimenters on the NASA spacecraft, and their US colleagues, were not!

There was much outcry. Not only for the loss of science, but also for the way it was done. There was a Memorandum of Understanding between NASA and ESA governing Ulysses, but like all MOUs it had an escape clause for the signatories, which NASA exercised. It was an unfortunate time in NASA for this event to occur. During the change in Presidential Administrations, there was no NASA Administrator in place who might have successfully reversed the cancel-
lation. And so it occurred, and influenced and clouded NASA-ESA relationships for years to come. Not to be burned like this again, ESA has insisted on more formality in its agreements than breakable MOUs for major cooperations with the US such as the International Space Station, and it has sought to maintain a vibrant Science Programme that is not dependent on the US.

The clean interface established early in the programme, with a separate ESA spacecraft, allowed the programme to continue, and since the US was still pro-
viding the launch and tracking, ESA honoured its commitments to the instru-
mentation that was being provided by the US for the ESA spacecraft, and the programme proceeded. However, like all spacecraft of that time, Ulysses was to be launched on the Shuttle, but the development of the Shuttle was delayed, and then the “Challenger” accident occurred, which delayed the launch still further. Not until October of 1990, sixteen years after that first meeting in ESTEC to design an exciting, cooperative mission between NASA and ESA, did Ulysses actually begin its journey to explore the heliosphere in three dimensions.
Lessons Learned for Cooperative Science Missions

There are lessons to be learned from the saga of Ulysses. First, the best science missions develop as grassroots efforts, where working scientists recognize an important scientific problem to be studied and conceive of a clever mission to pursue it. Second, important scientific problems are not the exclusive province of either Americans or Europeans, or other nations, and they are best pursued, whenever feasible, as an international adventure. Third, the scientific problem has to be of such importance that it remains central to the pursuit of a major science discipline for many decades, until the mission to study it is in fact realized. Fourth, there will be inevitable political obstacles that need to be overcome or worked around, which requires clever mission designs, and continuous vigilance and perseverance on the part of the science advocates of the mission.

When Johannes Geiss conceived of ISSI’s role in the international space-science effort in the early 1990s, these lessons of Ulysses had to be in his mind. If missions are to be based on recognition of an important scientific problem, there has to be agreement on what the state of that problem is – what is known and what is left, or indeed required to be discovered. The many ISSI books that summarize the state of knowledge of broad problems in space science very admirably serve this purpose. Important and lasting scientific problems require continuous nurturing, and the opportunity to discuss them over many years and many workshops is important. Scientists develop consensus on scientific knowledge and on missions to pursue, not in isolation but by interacting in person, and the many ISSI workshops and team meetings serve this purpose well. Perhaps most important is the international flavour of ISSI, and its full recognition that knowledge resides throughout the World. ISSI is founded on the principle that the best science and the best missions need to have access to the broad international capability.

It was perhaps fitting also that one of the significant conversations that led to the formation of ISSI occurred at the launch of Ulysses in 1990. Roget Bonnet, then Director of ESA’s Science Programme and now Executive Director of ISSI, and I, then the Associate Administrator of NASA, had the opportunity at the launch to discuss Johannes Geiss’s concept of ISSI. It was fitting that the lessons of Ulysses and the spirit of international cooperation that it engendered led to our both believing that this was a concept worth pursuing and endorsing.
The Scientific Discoveries of Ulysses

Each of the scientists who participated in Ulysses, and for that matter worked in solar and heliospheric physics, will have their own list of the most significant Ulysses discoveries. Below are the ones on my personal list.

We should note in passing that all of the significant discoveries that can be expected to be on anyone’s list have been a subject of discussion at an ISSI workshop, where their significance has been evaluated and their impact on broader science questions appreciated. At the very first ISSI workshop on The Heliosphere in the Local Interstellar Medium, which was a seminal event in our understanding of the interactions between our star the Sun and interstellar space, a central theme was interstellar neutral gas in the heliosphere, which was observed in detail by Ulysses, both as neutral particles and for the first time as pickup ions. In the workshop on Cosmic Rays in the Heliosphere, the observations from Ulysses were also central. The behaviour of cosmic rays in the heliosphere can only be understood as a three-dimensional problem, and without Ulysses little progress in this field would have been made. The workshop on Corotating Interaction Regions (CIR) was built around the Ulysses observations. Particles are accelerated in CIRs, stream-stream interaction regions in the solar wind that occur at low heliographic latitudes. Yet the accelerated particles were observed by Ulysses at high heliographic latitudes, indicating that a fundamental rethinking of the configuration of the magnetic field in the solar wind is required. In Solar Composition and its Evolution – from Core to Corona, the Ulysses observations of the composition of the solar wind, indeed the first such observations, were of primary importance.

There are three items that are high on my personal list of significant Ulysses discoveries. The first, which is highlighted above, is the composition of plasma particles in the heliosphere. It is important to note how primitive our measurements of the composition of the solar wind were prior to Ulysses. The Swiss foil experiments conducted by Johannes Geiss during the Apollo missions to the Moon in the 1960s gave us detailed information on the isotopic composition of the solar wind, but then only for a very brief period of time. Instruments of the time were routinely measuring the solar wind, separating particles only by their mass/charge ratio, with the result that sensitivity and resolution were relatively low; only a limited number of elements and charge-states could be uniquely determined. The SWICS instrument on Ulysses, designed by George Gloeckler, provided the first detailed and continuous observations of the composition of the solar wind, separating charge from mass, and of course performing these observations away from the Sun en route to Jupiter and over the wide range of latitudes and solar conditions observed by Ulysses.
The discoveries are many. By routinely determining the composition of the solar wind, the observations provided by SWICS unlock the power of composition measurements to understand fundamental solar processes. The elemental composition of the solar wind is biased according to the First Ionization Potential, or FIP, of its elements. A FIP bias must be established very close to the Sun, where the particles are just being ionized, and thus the FIP bias can be used to identify the regions on the Sun from where the solar wind originates. The charge-states of the solar wind are frozen-in in the corona of the Sun, and reveal the conditions under which the solar wind is being accelerated; there is a strong anti-correlation between the solar-wind speed and the coronal electron temperature as determined from solar-wind charge states. Coronal Mass Ejections, large eruptions of material from the Sun, contain plasma particles with unique charge states, and thus the composition measurements of SWICS on Ulysses provide a powerful identifier of remnant CMEs in the heliosphere.

Then there are the pickup ions. Prior to Ulysses, interstellar neutral gas was known to flow through the heliosphere. It was expected that the neutral gas would be ionized by charge-exchange with the solar wind and photo-ionization, and once ionized, it should be picked up by the solar wind and convected outward. This pickup-ion population should have a profound effect on the outer heliosphere. It is the dominant energy input into the solar wind, such that if this population were to remain separate from the core solar wind it would be the dominant internal pressure force in the solar wind beyond about the orbit of Saturn. Pickup ions were also predicted to be the source of Anomalous Cosmic Rays (ACRs), a component of the cosmic rays with an unusual composition that resembles the composition of interstellar neutral gas. For this to occur there must be a major acceleration process in the outer heliosphere, presumably at the termination shock of the solar wind, since pickup ions are formed with energies of ~1 keV/nucleon, but ACRs occur at tens of MeV/nucleon. Prior to Ulysses, however, the main species of the pickup ions had never been observed. There was evidence for pickup helium, since this species can penetrate as neutral to within the orbit of Earth, before being ionized and convected outward. However, the dominant pickup ion species, hydrogen, and such interesting species as oxygen, do not penetrate to within the orbit of Earth, and could only be observed and measured in detail by SWICS on Ulysses, for the first time, en route to Jupiter.

There is now an entire branch of science built around pickup ions. New sources have been discovered. Solar wind particles appear to become embedded in dust grains near the Sun, and are released to form a pickup-ion population known as the inner source. Comets emit neutrals that form pickup ions, and have an extended tail that can be observed, from which the composition of the comet can be determined. Interstellar neutral gas is a measure of the local interstellar
medium and thus the composition of the Galaxy in the present epoch, as opposed to when the Solar System was formed 4.5 billion years ago. The isotope helium-3 was measured in the pickup ions by Ulysses, and provides an important constraint on the evolution of baryonic matter in the Universe. All this from the pioneering measurements of SWICS on Ulysses.

The third item on my personal list of significant Ulysses discoveries is a much-improved understanding of the reversal in polarity of the large-scale magnetic field of the Sun, a fundamental solar problem.

Consider first solar-minimum conditions. At this time, the magnetic field at the poles of the Sun opens into the heliosphere and allows the escape of fast solar wind. The magnetic field is relatively strong in this region. As it opens into the corona, it comes into pressure equilibrium, with uniform field strength, and points radially outward as it is dragged outward with the solar wind. The polarity of the magnetic field at each solar pole is of course opposite. Once expanded into the heliosphere, the two regions of opposite polarity are separated by a single current sheet, which during solar-minimum conditions lies near the equatorial plane of the Sun.

At the next solar minimum, 11 years hence, the polarities in the two polar regions are reversed. The question is, how does this occur? The original theories for the field reversal of the Sun have new magnetic flux rising through the solar surface with the onset of solar activity, and then migrating to the solar poles such that the migrating flux has opposite polarity to that of the nearest solar pole. Flux annihilation occurs and the old polar flux is replaced by magnetic flux of opposite polarity. However, magnetic flux emerges in the form of closed magnetic loops. The magnetic field at the solar poles at successive solar minima opens into the heliosphere. How was the closed flux turned into open flux, and what should we have seen in the heliosphere?

Ulysses in fact observed a remarkably simple picture. That single current sheet separating the two regions of opposite magnetic polarity, which lies near the equatorial plane during solar minimum, appears to be preserved throughout the solar cycle. It simply rotates through 180 degrees to accomplish the field reversal. A single preserved current sheet has profound implications. Since the open magnetic flux can be eliminated from the Sun only by reconnection at the current sheet, and little reconnection seems to be occurring, there appears at some level to be a constancy to the open magnetic flux of the Sun. The field reversal, the formation and dissipation of coronal holes, all these will need to be accomplished by moving the open flux about on the Sun, presumably by moving it along the solar surface.
One final personal note. Over the last several years, I have written a number of papers about how the open magnetic flux of the Sun should behave and move about on the solar surface. The progenitor for this theoretical work was a paper explaining how motions of the open flux could distort the configuration of the heliospheric magnetic field, allowing energetic particles to propagate from CIRs at low latitudes to high latitudes where they were observed by Ulysses (the main subject of the ISSI workshop on Corotating Interaction Regions). The principal calculations for this progenitor theory were done on a plane ride to ISSI, for an entirely different workshop, where I was able to share my ideas with my colleagues, in off-line conversations, and get the feedback I needed to proceed – which is after all what ISSI is all about.

References