Directional Discontinuities in the Solar Wind:Ulysses Results

Johan De Keyser - Michel Roth - Joseph Lemaire
Johan.DeKeyser – Michel.Roth – Joseph.Lemaire@bira-iasb.oma.be

Belgian Institute for Space Aeronomy
Ringlaan 3
Brussels, 1180, Belgium

ABSTRACT

This paper reports on the activities of the Belgian Institute for Space Aeronomy as principal member of the Ulysses Interdisciplinary Study of Directional Discontinuities. This study focused on directional discontinuities in the solar wind, including both tangential discontinuities and rotational discontinuities, using data from ESA's Ulysses satellite, supplemented by observations from NASA's Wind satellite.

KEYWORDS

Solar wind, plasma discontinuities, Ulysses

INTRODUCTION

The solar wind is the outward extension of the solar corona. Coronal temperatures are so high that the plasma is no longer gravitationally bound: It can escape along the open magnetic field lines originating in coronal holes. The Earth is embedded in this streaming medium. The terrestrial magnetosphere reacts to the solar wind variations so that the interplanetary medium may induce strong changes in the Earth's space environment, in the atmosphere, and on the surface.

The solar wind is highly variable on timescales from seconds to years. We concentrate here on small-scale features in the solar wind known as directional discontinuities (DDs). These are surfaces across which the magnetic field abruptly changes direction. Regions of space filled with distinct plasmas always set up such interfaces. Understanding these interfaces is therefore a key element in understanding large-scale solar wind structure. DDs come in two flavours: tangential discontinuities (TDs), which are magnetic field-aligned surfaces across which there is no mass transport and which are convected with the solar wind flow, and rotational discontinuities (RDs), phase-steepened Alfvén wave fronts that are not field-aligned and that propagate relative to the ambient plasma. The distinguishing feature is the magnetic field component $\mathbf{B}_n$ perpendicular to the DD surface: it is zero for a TD, and nonzero (constant) for a (planar) RD.

This paper reports on the activities of the Belgian Institute for Space Aeronomy as member of the Ulysses Interdisciplinary Study of Directional Discontinuities:

http://www.oma.be/BIRA-IASB/ Scientific/Topics/SpacePhysics/Ulysses.html

It addresses issues regarding structure and evolution of DDs in the solar wind using data from ESA's Ulysses satellite, supplemented by Wind observations. Ulysses was launched ten years ago, in October 1990, and is still fully functional. From its high-inclination solar orbit, Ulysses was the first satellite that observed the solar wind over the Sun's poles and has thus been able to distinguish latitudinal variations in the solar wind . The paper reviews theory developments regarding DDs, and it addresses the relevance of theory for the interpretation of observations of the omnipresent small-scale solar wind DDs. Much attention is devoted to the heliospheric current sheet, which is a special discontinuity that separates the solar wind with opposite polarities coming from the northern and southern solar poles.

THEORY OF DISCONTINUITIES

The solar wind is essentially a fully ionized plasma. Most of the time it can be considered a collisionless plasma as well: It is so tenuous that particles have a very large mean free path. The physical description of a plasma is complicated because, at any time, each plasma particle is characterized by six variables: its spatial coordinates and velocity components. While in a magnetized fluid approach (like magnetohydrodynamic theory, MHD) moments of the velocity distribution functions (VDFs) are used to remove the dependency on the velocity components, kinetic approaches do take into account the specific shape of the VDFs but can quickly become intractable.

A kinetic model of TDs

The Rankine-Hugoniot conditions across DDs relate the plasma states on either side of a DD, without requiring or giving any information about the internal structure of the DD. This internal structure can only be resolved by examining the particle distributions. While TD structure is due to the nonzero gyroradii of the particles, MHD does not incorporate such small spatial scales and thus cannot be used to analyze such small-scale structure. A kinetic approach is therefore mandatory. In a planar TD each particle is characterized by three conserved quantities of motion (its energy and canonical momenta tangential to the discontinuity plane). Any VDF that can be expressed in terms of these quantities automatically satisfies the Vlasov equation, which describes particle behaviour in phase space. The problem is then reduced to solving a set of ordinary differential equations for the electricand magnetic potentials, which is not hard to do.

There is one difficulty: the solution to the problem of computing the equilibrium structure of a planar TD is not uniquely defined. One has also to specify how particles can access different regions of phase space. In principle, this information can be obtained by tracing back the origin of the particles in time (if one would regard the TD configuration as the result of some time-dependent process) or in space (if the planar TD is part of some larger, non-planar structure). In practice, we prescribe the form of the VDFs. Some flexibility is provided by parameterizing these VDFs. But is this prescribed form realistic? Of course, the VDF is not chosen arbitrarily: it is the product of a Maxwellian distribution and a so-called cutoff factor, which varies smoothly between 0 and 1. The cutoff factor is unity far on one side of the TD, so that the distribution is Maxwellian there (with boundary conditions specifying density, temperature, and mean velocity), and smoothly tends to zero on the other side, so that the particles cannot penetrate the TD very far. This is a very natural choice, that is able to reproduce some textbook transition layer examples. The transition length is a VDF parameter that determines the length scale over which the cutoff factor goes from one to zero; it is related to the transition thickness.

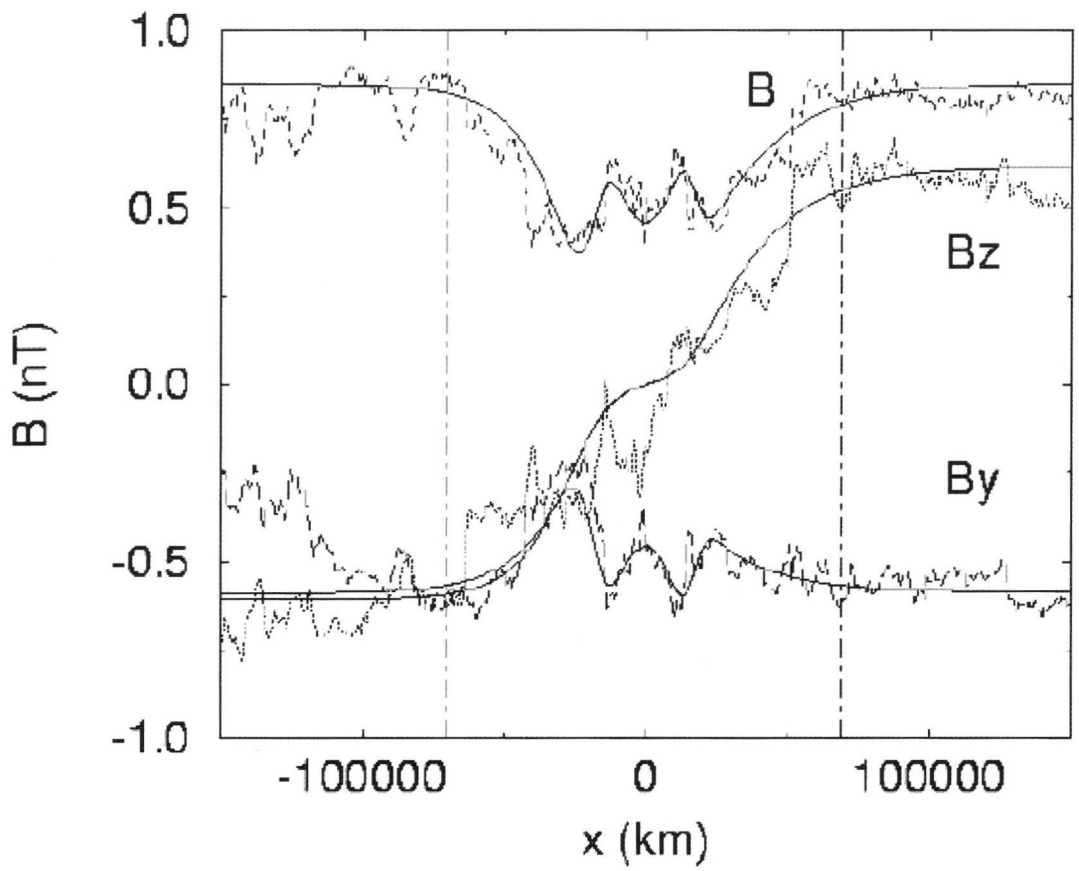

Figure 1: Observed (dashed lines) and simulated (solid lines) tangential magnetic field components (B_y and B_z) and magnitude (B) for a TD observed by Ulysses on July 3, 1993 in fast wind at 4.57 AU and -33.8° latitude.

The ultimate test is to attempt to reproduce actually observed solar wind TDs with this model. Ulysses magnetic field data are characterized by a high time resolution (1 vector/s) while the plasma data have a much lower resolution (12 minutes, a 3D VDF is obtained by scanning the sky during several revolutions of the spinning spacecraft); we can therefore constrain the TD model by using the field and plasma conditions observed on either side of the discontinuity, and by choosing the VDF parameters so as to reproduce the detailed magnetic field profile inside the TD. Figure 1 shows an example of such a reconstruction. Similar modelling has successfully been carried out for the TD magnetopause, which gives additional confidence in the model.

Velocity changes across discontinuities

The internal structure of DDs is determined to a large extent by the electric field. In addition to a charge-separation electric field due to the different gyroradii of the particle species involved, there is the convection electric field generated by the flow shear across the discontinuity layer. We have therefore analyzed the influence of the velocity change across a TD on the equilibrium structure of the TD using the kinetic model discussed above. We found that: (1) there exists a maximum flow shear, of the order of the ion thermal velocity, beyond which no equilibrium can exist; (2) the maximum flow shear strongly depends on the orientation of the velocity change relative to the magnetic field direction; (3) the maximum flow shear depends on the transition lengths of the ion and electron populations. An example of a flow shear domain for which TD equilibria exist, is shown in Figure 2.

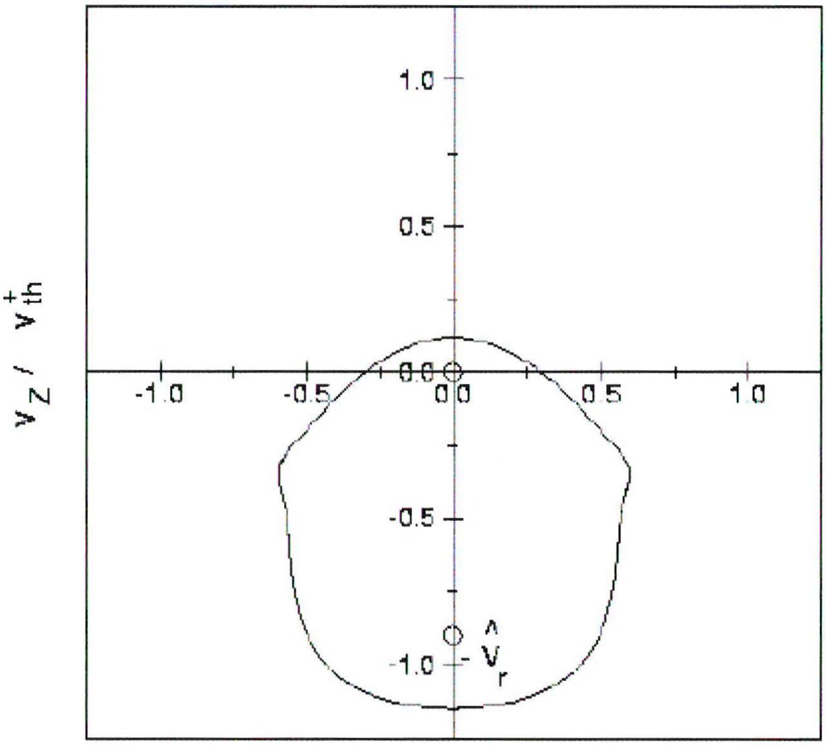

Figure 2: The closed contour demarcates the region of tangential velocity jump vectors for which TD equilibria exist, for β<4 and a magnetic field rotation of 90°, and for ion and electron transition lengths $L_+=5\rho^+ > L_-=\rho^+$. The maximum flow shear is of the order of the thermal ion velocity V^+_{th} but depends also on the shear direction.

For RDs there is no general kinetic description available. There is, however, the Walén relation that links the magnetic field and velocity changes across an RD. The existence domains that we found for TDs are compatible with the Walén prediction for RDs with small $\mathbf{B}_n$.

OBSERVATIONS OF SOLAR WIND DISCONTINUITIES

Satellite observations have established that small-scale DDs occur very frequently in the solar wind. The apparent decrease of DD occurrence rate with radial distance can be accounted for by selection effects of DD identification criteria; the majority of DDs seems to be formed inside 1 AU. DD occurrence rates are different in solar wind streams, corotating interaction regions, and polar coronal holes.

Discontinuities at low latitude

The relation between RDs and Alfvén waves in the solar wind has been explored extensively in the past. We have therefore focused on the TDs. DDs are observationally classified as TDs when $\Delta|\mathbf{B}|/\mathbf{B}_{max}=0.2$ and $\mathbf{B}_n/\mathbf{B}_{max}=0.4$, where $\mathbf{B}_{max}$ is the largest of the magnetic field strengths on either side of the DD. We have examined the tangential magnetic field and velocity jumps (actually $\Delta\mathbf{B}_t/\rho$) and $\Delta\mathbf{V}_t$ across such DDs (which can actually be of TD or RD nature), observed in April 1995 by NASA's Wind satellite in slow and fast solar wind streams at low heliolatitude during low solar activity . We found that the magnetic field rotation sense in fast wind DDs is as predicted by the Walén relation for outward propagating RDs, but the flow shear magnitude and orientation do not always agree well with the theory. Alternatively, DDs with small normal magnetic field can be regarded as TDs; we found that the observed shears imply that the proton transition length can be both smaller or larger than the electron transition length.

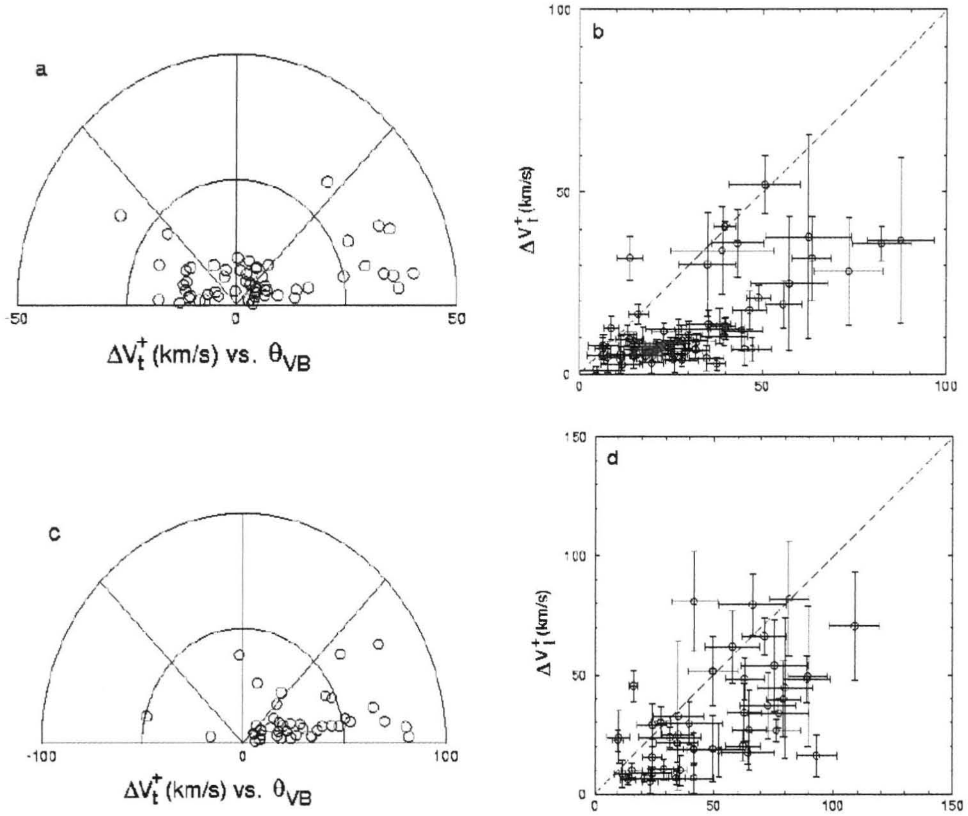

Figure 3: Statistical analysis of the Walén relation that links the observed ion flow ΔV_t^+ across DDs with the predicted value ΔV_{tp}^+, which is obtained from the change in magnetic field and density across the TD, from the B_n, the temperature anisotropy, and the average density. Top row: Slow wind: (a) Polar diagram of observed flow versus polar angle θ_{VB}, the angle between the observed flow and magnetic shears. For RDs, this angle should be 0° or 180°. (b) Observed flow shear magnitude ΔV_t^+ versus the value ΔV_{tp}^+ predicted from the Walén relation; there is a significant mismatch. Bottom row: Fast wind: (c) The polar diagram shows that field and flow shear are mostly parallel. (d) The Walén diagram is largely consistent with RD behaviour.

We found that the slow wind includes a larger fraction of DDs that disagree with RD theory than does the fast wind (Figure 3). Note that these statistics do not include the observationally labeled RDs, but only the observational TD class. These observationally classified TDs, especially in the fast wind, appear to behave very much like RDs or Alfvén waves. This Alfvénic nature was already noted before. A tentative explanation for this behavior is the following. Particles downstream of an RD originate from the upstream side; their properties are determined by the jump conditions. As the RD propagation speed decreases (smaller $\mathbf{B_n/B}$), particles need more time to drift across the layer and can be affected by other phenomena (e.g., diffusion due to microturbulence), resulting in a lower velocity jump magnitude than predicted. Plasma differences observed across a DD reflect source region properties for small $\mathbf{B_n}$ only and close to the source. The Alfvénic nature of these DDs therefore suggests that most solar wind DDs with small $\mathbf{B_n}$ should still be considered RDs rather than true TDs: They are phase-steepened large-amplitude Alfvén waves that happen to propagate slowly as their wave vector is nearly perpendicular to the field. There is a larger fraction of deviations from the RD relation as well as a larger proportion of small $\mathbf{B_n/B}$ DDs in the slow wind, indicating the presence of a significant number of field-aligned current sheets (including heliospheric current sheet crossings).

Discontinuities at high latitude

In a series of case studies we have examined the effect of flow shear on TDs in the fast wind emanating from the polar coronal holes during solar minimum, as observed by Ulysses. The major reason for doing this is that Ulysses found this polar solar wind to be very homogeneous: As there are not many density or temperature changes, the flow shear and its associated convection electric field is the major factor responsible for DD internal structure.

Figure 4 shows an example of such a case study where the internal structure has been reconstructed by the kinetic TD model. We found that small velocity changes (hardly observable, and certainly not by Ulysses with the very low time resolution of its plasma instrument) are sufficient to produce these TDs. We also found that the electric fields produced by such flow changes can occasionally ``bunch" particles together, thereby locally increasing the thermal pressure and, because of pressure balance, depressing the magnetic field into a ``magnetic hole" structure.

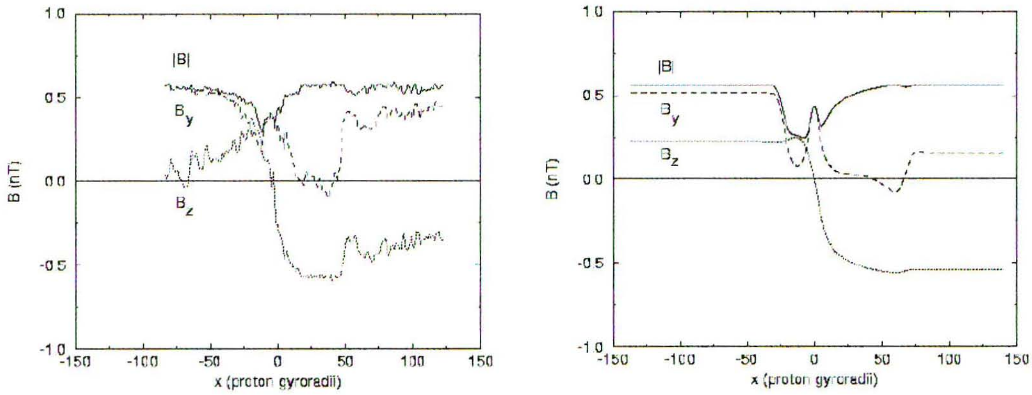

Figure 4: Observed (left) and simulated (right) magnetic field for a fast wind TD across which there is a velocity change of ≈10 km/s, or 1/4th of the thermal ion velocity. This TD was observed by Ulysses on July 3, 1993 at 4.6 AU and –34° latitude.

THE HELIOSPHERIC CURRENT SHEET

The heliospheric current sheet (HCS) is the surface separating the regions of inward and outward magnetic field lines originating in the polar coronal holes at solar minimum. Near solar maximum, it is not clear whether such a single current sheet does exist, or rather a set of sheets surrounding open field line regions corresponding to coronal holes that can occur at all latitudes. The HCS is the extension of the heliomagnetic equator into interplanetary space. As it separates solar wind regions with different origins, it is generally of TD type. Near solar minimum the HCS is a gently undulating surface. As the ecliptic is slightly inclined to the solar equator, the Earth is submerged alternatingly in solar wind originating in the northern and southern hemispheres, which have opposite magnetic polarities. Regions of a given polarity are called sectors; they are separated by HCS crossings which are therefore also known as sector boundaries.

Large-scale structure

We have studied sector boundaries observed by Ulysses at aphelion (5.4 AU). At that time (beginning of 1998) Ulysses was nearly radially aligned with Wind at 1 AU. A direct comparison of Wind and Ulysses data is not easy, but with the help of a spherically symmetric hydrodynamic simulation we were able to relate corresponding observations of interaction regions. Such a simulation indicates where dynamic solar wind evolution is important, but it fails to correctly predict this evolution as it does no account for the proper geometry and as it neglects the role of the magnetic field. Such a model can be used to reconstruct qualitatively the 3D shape of the HCS, as illustrated in figure 5.

Starting from the sector structure observed at 1 AU, this simulation predicts sector boundary location at 5 AU reasonably well except in the presence of strong transient phenomena. This is shown, for a typical sector, in figure 6. The general similarity in sector structure that we observe between 5 and 1 AU supplements the good correspondence between 1 AU sector boundaries and source surface predictions of the neutral line: The sector pattern in the entire inner heliosphere is well correlated with the coronal field during this period of modest solar activity. Similar conclusions regarding the macroscale coherence of the heliospheric current sheet were reached from a Pioneer 10 and 11 radial alignment studies at 1 and 2 AU. For most Ulysses sector boundaries we were able to identify a corresponding Wind sector boundary. Although the solar wind evolves considerably between 1 and 5 AU, and in spite of the change of the Parker spiral angle from 45° to 80°, we observe strong similarities in the large-scale appearance of these sector boundaries. In some cases we did not find a corresponding 1 AU sector boundary, but a magnetic cloud structure with nonspiral magnetic field; the deformation of the HCS by coronal transients appears to be only temporary.

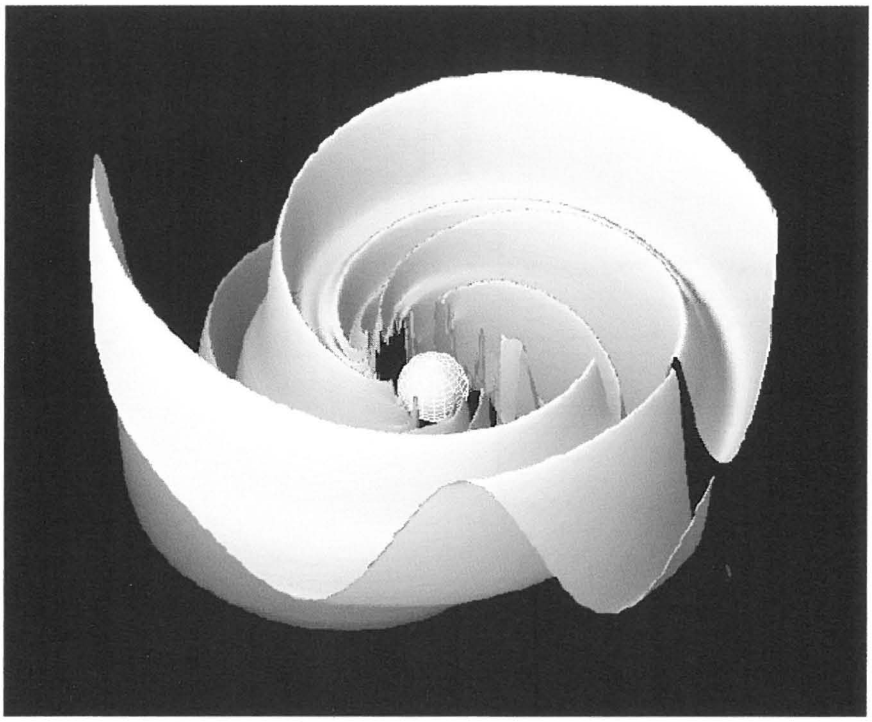

Figure 5: Qualitative reconstruction of the HCS surface between 1 and 5 AU. The plot is based on a spherically symmetric hydrodynamic simulation using 1 AU Wind data for February 1998 as inner boundary condition. Temporal changes are interpreted as longitudinal variations, and the latitudinal excursion of the HCS is assumed proportional to the cosine of the angle between the magnetic field vector and the Parker spiral direction, with an arbitrary scaling factor (chosen so as to obtain realistic latitudinal HCS excursions). The "cut" in the plotted surface separates data one solar rotation apart; the degree to which the surface matches across the cut indicates the overall persistence of solar conditions during this rotation. Note that the size of the solar sphere is exaggerated.

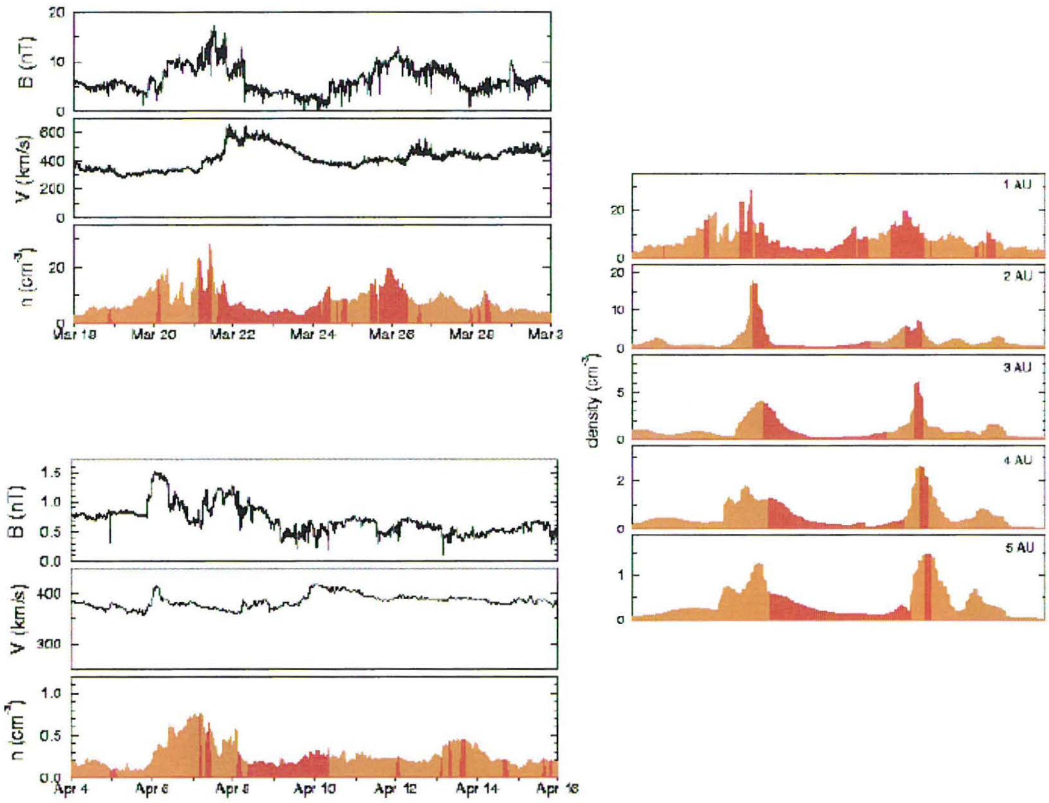

Figure 6: Evolution of an outward sector from 1 to 5 AU. (a,top) Wind observations at 1 AU. (b,middle) Hydrodynamic simulation between 1 and 5 AU. (c,bottom) Ulysses observations at 5 AU. Yellow shading indicates inward magnetic field polarity; red shading indicates outward polarity.

Small-scale structure

The Ulysses encounters with the HCS are embedded in a high-beta heliospheric plasma sheet (HPS), which is characterized by pressure balance as at 1 AU, consistent with the picture of a HCS as TD contact surface between winds of different origin. The main part of the HCS transition typically is less than 100 ion gyroradii wide, although the full transition seems an order of magnitude wider. The fact that the magnetic field vector in nonmonotonous polarity reversals traces essentially a single curve in the tangential magnetic field hodogram, as in figure 7 supports the concept of a rippled HCS, as illustrated in figure 8. This concept was advanced earlier to explain the observation of multiple, closely spaced HCS crossings. Calculations show that the sheared flow configuration near the HCS can excite kink mode instabilities; ripples in the HCS could be identified with such kink waves. The presence of ripples, in combination with geometrical effects, can explain the observed variability in sector boundary appearance and width. A multiple-current-sheet sandwich structure can in general not be excluded, but such a structure cannot account for the properties of the hodogram of figure 7.

Even accounting for a curved geometry, HCS thickness (tens of ion gyroradii to 100 ion gyroradii) remains typically larger than that of general solar wind TDs (1--30 gyroradii). Sector boundaries are a particular TD population characterized by large magnetic field rotations. The small-scale structure of the Ulysses sector boundaries exhibits magnetic field depressions as at 1 AU (like those observed at the high-shear dayside magnetopause), which we associate with the drifting ions and electrons inside the TD layer that produce the net current required for the rotation of the field. The limited plasma data resolution available on Ulysses did not allow us to study this fine structure in more detail.

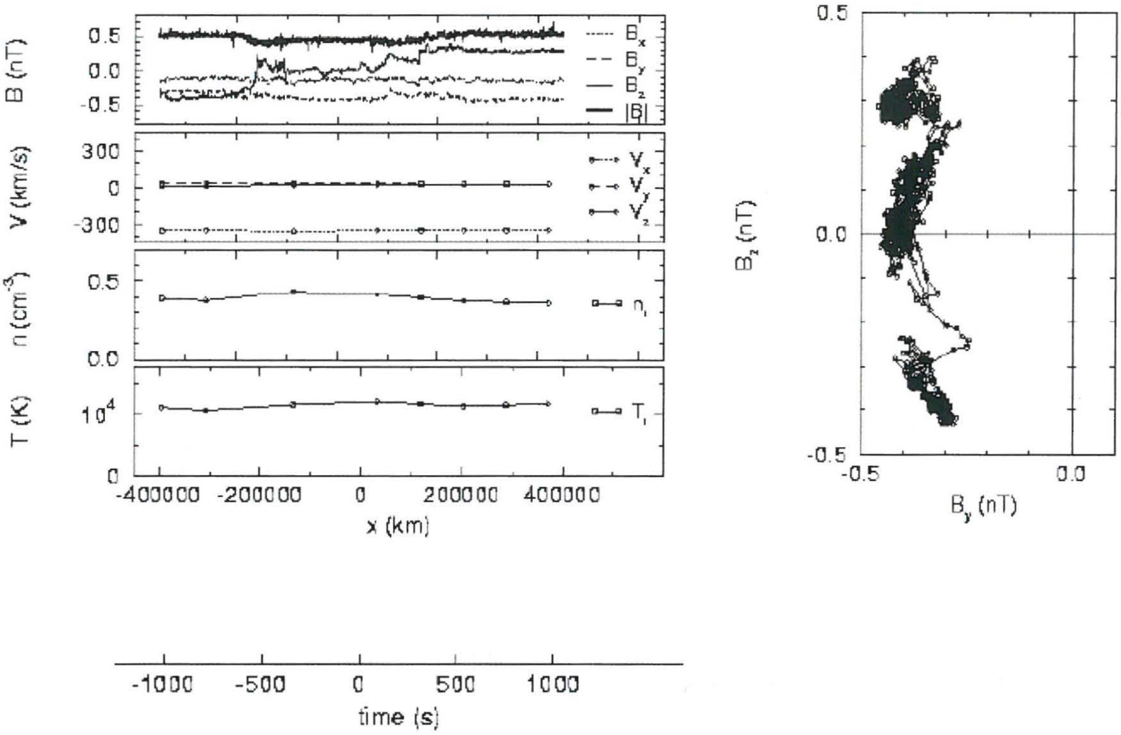

Figure 7: Sector boundary observed by Ulysses on January 7--8, 1998. Left: Magnetic field and solar wind velocity in the minimum variance frame; the horizontal axes give the time elapsed since observation of the center of the structure and the corresponding distance. Right: Hodogram of the tangential magnetic field vector.

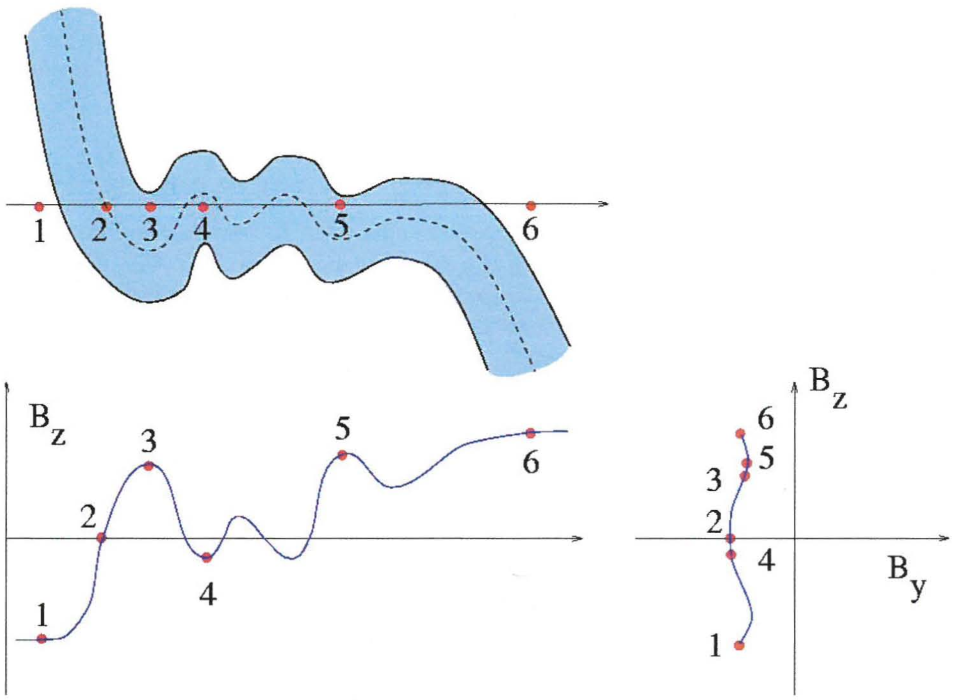

Figure 8: Crossing of a folded current sheet and its appearance in the minimum variance frame. The true thickness of the current sheet is much less than its apparent width. The tangential magnetic field components trace a single curve in the B_y-B_z hodogram.

Formation of the heliospheric current sheet

The tangential magnetic field in the HPS and HCS layers implies that particles are confined or trapped in these structures: The particles move parallel to the layer. The similarity between 1 and 5 AU sector boundaries indicates that the overall shape of the HCS is conserved while the solar wind expands. No major instability seems to develop, which would obscure the similarity. The origin of the trapped particles must therefore be sought closer to the Sun. Because of the correspondence with source surface maps we expect this trapping to take place inside the corona. This is supported by the often observed double ion beams near the HCS, which have been related to a coronal origin as well. Once formed, the HCS structure changes in a quasi-static manner on its outward journey into interplanetary space.

CONCLUSIONS

This paper reports on the activities of the Belgian Institute for Space Aronomy as principal member of the Ulysses Interdisciplinary Study of Directional Discontinuities. This study addressed the structure and evolution of directional discontinuities in the solar wind, using data from ESA's Ulysses satellite, supplemented by Wind observations. The major results are:

1. The internal structure of tangential discontinuities can be fully understood and modeled in terms of kinetic theory.
2. There exists a relationship between velocity and the magnetic field changes across a tangential discontinuity, which is an extension of the Walén relation for rotational discontinuities.
3. Solar wind tangential discontinuities often resemble rotational discontinuities, especially in the fast wind, with the difference that they propagate in a direction nearly perpendicular to the magnetic field; the dividing line between both classes is not very sharp.
4. Tangential discontinuities are found mostly in the slow wind; the fast wind is filled with Alfvén waves and rotational discontinuities; this has been verified by means of the Walfvén relationship.
5. Small velocity changes in the fast solar wind emanating from polar coronal holes are sufficient to produce the tangential discontinuities and magnetic holes observed there.
6. The heliospheric current sheet most often is a tangential discontinuity. Its large-scale structure varies smoothly as the equatorial solar wind expands outward. Its internal structure shows variability on a broad range of distance scales; we have found that this can be understood in terms of one undulating current sheet (or possibly a few) of gyroradius thickness scale.

ACKNOWLEDGEMENTS

We are strongly indebted to the Ulysses Science Team, in particular, R. Marsden and E. Smith, the ESA and NASA Ulysses project scientists, M. Schulz (Lockheed-Martin, Palo Alto, CA, USA, co-PI in the Interdisciplinary Study of Directional Discontinuities), A. Balogh and R. Forsyth (Imperial College, London, UK, Ulysses magnetometer), B. T. Tsurutani (JPL, NASA/Caltech, Pasadena, CA, USA, Ulysses magnetometer), C. M. Hammond, J. L. Phillips, D. McComas, D. Reisenfeld, and J. Gosling (Los Alamos National Labs, NM, USA, Ulysses plasma experiment), R. Lepping and K. Ogilvie (NASA/GSFC, Greenbelt, MD, USA, Wind magnetometer and plasma experiment), and A. S\"{o}ding (Universit\"{a}t K\"{o}ln, Germany, Ulysses Guest Investigator). We also acknowledge the support by ESA-PRODEX and by the Belgian Federal Services for Scientific, Technological and Cultural Affairs, who enabled us to participate actively in the Ulysses project.

FUNDING SOURCES

This work was funded by PRODEX Ulysses (primary contract in 1994--1998, follow-up until 2000).

BIBLIOGRAPHY

This bibliography section only covers solar wind research; related material can be found in our contributions to the Magnetospheric Physics section.