Directional discontinuities in the interplanetary magnetic field

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Abstract

Directional discontinuities of the interplanetary magnetic field are ubiquitous features in the solar wind. A key issue has been the identification of the nature of these discontinuities: Are they tangential discontinuities, i.e., surfaces separating plasmas of different densities and temperatures (and, possibly, composition), or are they rotational discontinuities, where the plasmas on the two sides are magnetically connected, and densities and temperatures are, to first order, the same. The answer has important implications for the topology and origin of the interplanetary magnetic field, but is also of practical significance, because it could affect the propagation delay between the observation at an upstream monitor and the arrival at the Earth's magnetopause.

The primary quantity used to distinguish rotational from tangential discontinuities is the magnitude of the normal magnetic field components. Based on discontinuity orientations inferred from minimum-variance analysis of single-spacecraft magnetometer data, past studies had concluded that a large fraction of the directional discontinuities had normal components much in excess of zero, and thus should be identified as rotational discontinuities. With the advent of ESA's Cluster mission, it has been possible to determine the discontinuity orientation, from the crossing times recorded by the four spacecraft. In a seminal paper, *Knetter et al.* (2004) demonstrated that, based on the timing normals, the normal components were zero within error estimates for all discontinuities they investigated. Their results were thus consistent with an interpretation that the solar wind is dominated by tangential discontinuities, in striking contradiction to the earlier studies.

Using the large set of directional discontinuities identied by Thorsten Knetter in the Cluster data, we propose to focus our investigation on four interrelated topics that are of prime importance for the understanding of the nature of solar wind directional discontinuities, but require the advanced analysis techniques members of the team have developed.

The first goal is to put Knetter's result concerning the absence of rotational discontinuities on a firmer footing, by establishing tighter limits on the normal components, using a new method to quantify the four-point timing uncertainties, as described in ISSI SR-008. We will thus be able to confirm or refute the basic conclusion about the nature of the solar wind directional discontinuities.

The second goal concerns the occurrence of Alfvénic fluctuations. In a preliminary analysis we have established that a large fraction of the directional discontinuities are embedded in a sea of magnetic field and plasma flow fluctuations that closely match the requirements for Alfvén waves, as evidenced by successful tests of the so-called Walén relation. We will look in detail at the propagation direction of these Alfvénic disturbances relative to the ambient magnetic field, using the wave surveyor technique developed by a member of the team.

The third question addresses the Alfvénic nature of the directional discontinuities themselves. We have already identified a subset of directional discontinuities that are sufficiently resolved in the plasma measurements so that the Walén test can be applied to the samples within the directional discontinuities themselves. The results support the conclusion that they were RDs. Related to this issue is the suggestion that the well-defined Alfvénic fluctuations surrounding the directional discontinuities could have played a role in the formation of the directional discontinuities via nonlinear wave steepening. This process appears to lead to structures in which a very gradual field rotation either precedes or follows a directional discontinuity, which rapidly rotates the field in the opposite sense back to its original direction. We have already identified a number of such cases, and intend to establish their properties by use of the array of analysis tools at our disposal.

The striking failure of the minimum variance analysis technique to infer the normal directions of the directional discontinuities and the differences in the profiles often recorded by the four spacecraft, suggest an internal structure and/or temporal evolution of the directional discontinuities. As our fourth goal, we will therefore search for such local structures, employing two novel techniques. One is the magneto-hydrodynamic (MHD) reconstruction technique, developed by members of the team, that allows reconstruction of two-dimensional coherent MHD structures from time-series of magnetic field and plasma data. A second approach will be based on the lag-covariance matrix of the multivariate spacecraft measurements, which allows determination of the percentage of the magnetic field profiles that cannot be explained by the hypothesis of a one-dimensional time-stationary structure convecting past the four spacecraft.

To facilitate the work at the team meetings, we have started to compile, in the format of a large spreadsheet, all the results that we have obtained for all the directional discontinuities. This will provide a convenient means to filter the data for certain combinations of properties that we want to focus on.

1 Background

The direction of the interplanetary magnetic field is constantly changing, sometimes gradually, but frequently in the form of nearly discontinuous jumps, referred to as directional discontinuities (DDs). Many questions surround this topic, but we will focus on the investigation of their local properties, based on the four-point measurements by the Cluster mission. To understand the nature of the DDs has been a long-standing issue in solar wind research: Are they tangential discontinuities (TDs), i.e., surfaces separating plasmas of different densities and temperatures (and, possibly, composition), or are they rotational discontinuities (RDs), where the plasmas on the two sides are magnetically connected, and densities and temperatures are, to the first order, the same. So far the outcome has been inconclusive, as summarized by *Neugebauer* (2006).

In principle, it should be straightforward to distinguish between TDs and RDs by simply determining the component, B_n, of the magnetic field across the discontinuity surface. For TDs this component should be zero, and for RDs non-zero. To determine B_n requires knowledge of the orientation of the DD, which has traditionally been obtained by Minimum-Variance Analysis (MVA) of the magnetic field (e.g., *Sonnerup and Scheible*, 1998). Using this and other single-spacecraft methods, a number of DDs were classified as RDs. With the advent of four-point measurements by the Cluster mission, it has been possible for the first time to obtain estimates of the DD orientation from the differences in crossing times at the four spacecraft, together with their known position in space. In a seminal study of 129 carefully selected DDs observed by Cluster in 2001, *Knetter et al.* (2004) found that many events met the requirement of an RD when the calculation of B_n was based on the normals from MVA, while none remained when B_n was calculated from four-point timing. A similar trend towards small B_ns had already been reported by *Horbury et al.* (2001) based on Geotail, Wind and IMP8 timing. These results demonstrated that there can be fundamental problems with the use of MVA for determining normal directions. In his thesis, *Knetter* (2005) extended his study to include events in 2002 and 2003. The basic conclusion that none of the DDs met the traditional requirements for an RD, namely a B_n value significantly different from zero, remained. In fact, Knetter concluded that "$|Bn|/Bmax = 0$ within errors for all DDs in our data set." The predominance of small B_n values has also been reported in a recent statistical study of DDs observed by Ulysses (*Erdös and Balogh*, 2008).

A different approach towards distinguishing TDs and RDs is based on checking the RD jump relations across the DDs, according to which the flow, as seen in the proper frame, should be field aligned and Alfvénic. This approach also has a long history in solar wind research, but the outcome has again been inconclusive (*Neugebauer*, 2006). This is because it has been argued that TDs, on their way from the Sun might evolve such that only those with aligned flow-velocity and magnetic field variations survive, possibly as a result of the Kelvin-Helmholtz instability (*Neugebauer*, 1985). This alignment is a key prediction of the RD jump relation. Why the magnitude of the flow variations should approach the Alfvén velocity is, however, not clear.

Another important issue, highlighted by the availability of four point measurements, is the local structure of the solar wind DDs. In most analysis approaches the DDs convected across the spacecraft are assumed one-dimensional and time-stationary. But simple inspection of the four magnetic-field time series often reveals differences indicating that, even on the short spatial and temporal scales of Cluster, the solar wind DDs are neither. The discrepancies between the normal vectors determined from timing and from MVA are also suggestive of localized structures, such as magnetic islands, that could easily contaminate the MVA results.

There are other important issues, such as the question of the origin and evolution of the solar wind DDs, their occurrence in different types of solar wind, aspects of plasma composition, and others, but those are beyond the scope of our proposed project.

2 Goals of the project

We propose to address the open issues of the nature of the solar wind DDs based on the large set identified by Knetter. Although he no longer works in the field, he has kindly provided us with lists specifying the times of the DDs and the normal directions from his timing analysis, as well as those from MVA.

Normal components of the magnetic field Based on Knetter's timing normals, 121 of the 190 cases in 2003 have normal magnetic field components, B_n, of less than 0.5 nT, and only 27 of the 190 cases have B_n magnitudes in excess of 1 nT. To determine whether any of these are significantly different from zero and thus meet the requirements for an RD, requires precise knowledge of the angular errors in the normal directions. Noting that a true TD, with a total field of 5 nT, may appear as having a normal field component of almost 0.5 nT if the normal has an error of only 5 °. Thus angular accuracies of better than 5 °are required.

For normals from four-point timing, the errors derive from the uncertainties in the relative crossing times, while the uncertainties in spacecraft position are so small that they can be safely ignored. In his thesis, Knetter included a simple error analysis, which led him to conclude that all the B_n values emerging from his data set were zero within errors. However, we believe his error analysis may systematically overestimate the errors. We are presently experimenting with a method to calculate the uncertainties in the relative timing by use of an estimate of the standard deviation of the time lag, given by Eqn. (1.7) in ISSI SR-008 (*Sonnerup et al.*, 2008a), the expectation being that a smaller error estimate will emerge. Once the timing errors have been quantified, normals are computed for all combinations of relative crossing times falling within those error windows. From this set, the average normal and its error ellipse are calculated, from which the errors in B_n directly follow, as described in Eqn. (8.24) of ISSI SR-001 (*Sonnerup and Scheible*, 1998). We have already tested this procedure.

The timing method assumes that the same signal is recorded at the four spacecraft, with just a shift in time. In this situation, large inter-spacecraft distances, with their associated larger separations in crossing times, would be best. But localized internal structures and temporal evolution of the DDs can invalidate this assumption. The resulting adverse effects on the accuracy of the normal field component may actually increase with increasing inter-spacecraft separation because of the longer time available for the temporal evolution. We will be able to investigate these conflicting effects because our data set covers a wide range of separations. In 2001, 2002, and 2003, the average separations are 940, 160, and 3860 km. We will also exploit new methods for determining normal directions, one based on a mixed timing and MVA analysis, the other on the reciprocal vector technique. Both methods are designed for the case of three spacecraft. These methods are briefly mentioned in SR-008 (*Sonnerup et al.*, 2008a; *Vogt et al.*, 2008), but have been further developed since (*Teh et al.*, 2009; *Vogt et al.*, 2009). They can be applied to the four possible combinations of three spacecraft that Cluster permits, which will allow us to study the role of the spacecraft configuration on the outcome.

Overall, we will be able to better establish the uncertainties in the resulting normals and implied B_ns. This should enable us to confirm or refute the claim that none of the cases meet the RD requirement of a significantly nonzero magnitude of B_n. As discussed further below, there are other features of RDs that may allow their identification even if B_n is too small to be measured with sufficient accuracy.

DD speeds The four-spacecraft timing analysis provides not only the DD normal, but also its speed, which can be compared with single-spacecraft estimates, such as the component of the deHoffmann-Teller velocity along the normals. We will evaluate the causes for any discrepancies between the various speed estimates.

Alfvénic fluctuations Simple inspection of the time-series of plasma flow velocity and magnetic field components surrounding the DDs indicates that the velocity and field variations are often well correlated or anticorrelated, suggestive of Alfvénic fluctuations. A good way to demonstrate this behavior quantitatively is to transform the measured plasma velocities into the deHoffmann-Teller (HT) frame and then compare them, component by component, with the corresponding measured Alfvén velocities (e.g., *Paschmann and Sonnerup*, 2008, in ISSI-SR008). We already have applied this test, commonly referred to as the Walén-relation test, and illustrated in Figure 1, to the entire set of 190 DDs in 2003. We found flow speeds in the HT-frame that were better than 70% of the Alfvén speed in 91 (almost 50%) of the cases, and better than 80% in 48 (25%) of the cases. From the sense of the correlation, and the pitch-angle at which the electron-Strahl occurs, we have already established that the Alfvénic fluctuations are propagating in the anti-sunward direction, except for 9 cases where the Strahl pitch angle was not clear. From MVA, the propagation direction appears to be roughly parallel to the DD surfaces and more or less along (or against) the magnetic field.

We will look in detail at the propagation direction of the Alfvénic disturbances surrounding the DDs, relative to the ambient magnetic field, using the new wave surveyor technique (*Vogt et al.*, 2008). It extracts only the dominant wave mode from the four- spacecraft data, but is much faster than existing techniques (such as k-filtering) and hence is better suited to the analysis of our large data set. We will also study the wave-polarization, using the magnetic hodograms from the MVA.

Nature of the DDs One problem with applying the Walén-based approach to the DDs themselves is the limited time resolution of the plasma measurements. Applying the Walén relation successfully across an unresolved DD does not constitute direct evidence that the DD is an RD, because it could be mimicked by a TD that is embedded in Alfvénic disturbances on both sides. The existence of a good deHoffmann-Teller frame does not help either, because one can always find such a frame for a TD (*Paschmann*, 1985). In 8 of the 48 cases with good agreement, however, the DD was sufficiently resolved in the plasma measurements for the Walén test to be meaningfully applied. The results support the conclusion that they were RDs, although for unexplained reasons the flow speed remained at only 80 - 90% of the Alfvén speed. By including the DDs from 2001 and 2002, we will certainly increase the number of events that allow the Walén test to be used. Note also that the failure to resolve a DD does, of course, not preclude that it could be an RD.

The presence of well-defined Alfvénic fluctuations surrounding many of the DDs suggests that they could have played a role in the formation of the DDs via nonlinear wave steepening, a process that has been discussed extensively in the literature (e.g., *Vasquez and Hollweg*, 1996). This process appears to lead to structures in which a very gradual field rotation, embedded in a sea of Alfvénic fluctuations, precedes a DD, which rapidly rotates the field in the opposite sense back to its original direction. The reverse order also occurs: An example taken from the Knetter data set is shown in Figure 2, but the existence of such rotational structures, referred to as 'arc-polarized', has been known for some time (*Riley et al.*, 1996; *Tsurutani et al.*, 1997; *Horbury and Tsurutani*, 2001). There may be a tendency for these structures to repeat themselves, forming a nonlinear wave train. Although we are not able to study the steepening process itself, we have identified a number of cases that fit this pattern and intend to establish their properties by use of the array of analysis tools at our disposal. Of particular interest is the normal field and flow, both of which are small, and from them the propagation direction and polarization of the rapid and the slow field rotations. Detailed documentation of this type is still rather incomplete in the literature. In this case the small normal field component, combined with the fact that both sides of the structure are likely to be magnetically connected to the sun, precludes the use of Strahl for determination of the propagation direction of the DDs.

Local structure within the DDs The many DDs that show differences in the magnetic field profiles recorded by the four spacecraft must have an internal structure on the relatively short scales of Cluster. The noted systematic differences between the timing and MVA normal directions also suggest the occurrence of local structures. The very different separations between the Cluster spacecraft in 2001, 2002 and 2003 (940, 160, and 3860 km on average for the events in these years), will allow us to investigate the scale-sizes of these structures and/or look for evidence of temporal evolution, based on two independent methods. One is the MHD reconstruction technique (*Sonnerup and Teh*, 2008; *Sonnerup et al.*, 2008b; *Teh and Sonnerup*, 2008; *Teh et al.*, 2009) that allows reconstruction of two-dimensional coherent MHD structures from time-series of magnetic field and plasma data. Figure 3 in the Appendix shows the map from one of the DDs in our data set. Such maps will tell us whether small-scale magnetic islands (flux ropes) are responsible for the differences observed by the four spacecraft. The technique requires the DDs to be sufficiently well resolved in the plasma measurements, although the use of suitable data interpolation will in some cases be possible and allow low-pass-filtered maps, sufficient for our purposes, to be recovered.

A second approach will be based on the lag-covariance matrix of the multivariate spacecraft measurements. Traditional multivariate correlation techniques like the MVA or the Principle Component Analysis are based on an eigenstructure decomposition of the data covariance matrix at zero lag. The main component then gives a reference signal that is expected to explain a significant fraction of the overall variance in the data set, and in practice can be considered as an average of the individual time series. However, even non-dispersive plasma structures that are passively convected over the Cluster tetrahedron can be modeled only if non-zero values of the lag at the different spacecraft are considered, and an approach that unifies MVA with the spacecraft timing analysis is required. This can be conveniently achieved in Fourier space where the time domain lag-covariance matrix becomes the cross-spectral density (CSD) matrix. The wave surveyor technique, already mentioned above, is based on a rigorous eigenstructure analysis of the CSD matrix, and further on an interpretation of the eigenvectors in terms of plasma wave modes. Backtransformation of the dominant eigenmode to the time domain then yields the plane wave contribution to all signals, and the residual is a measure of the local structure that cannot be explained by the passive convection model.

There is an important feedback from the analysis of the local structure onto the studies based on precise knowledge of the normal directions. This is because, as noted above, the timing method assumes that the same signal is recorded at the four spacecraft, with just a shift in time. Localized structures invalidate this assumption and we want to establish how serious this problem is.

Timeliness of the project We have already compiled a large set of DDs and performed extensive analyses on all of them. So we are ready to start the project immediately, and are confident of a positive outcome. Since the experience with the existing methods, and some new and yet untested methods, have just been reported in ISSI's publication SR-008 (Multi-Spacraft Analysis Methods Revisited), to which all team-members contributed, and also in some more recent articles by team members, turning this accumulated experience onto the important issue of the nature of solar wind discontinuities seems very timely.

Expected output A number of original articles in refereed journals will result, possibly separated according to methodological and science issues. Here is a tentative list: *Solar wind DDs and Alfvénic fluctuations; Solar wind discontinuity classification based on magnetic field normal components; Local structure of solar wind DDs; Accuracy of the discontinuity-normals from four-spacecraft triangulation.*

Added value The nature of solar wind DDs has become highly controversial, requiring the pooling of all known tools to make progress, including several tools that have never been applied to real data. This will require extensive face-to-face discussions of the material prepared in advance, of new ideas developed at the meetings, and of the underlying controversies. This makes our topic well suited for an ISSI team.

3 Organization

Team members and their responsibilities For the first meeting, the team composition is as follows. All have confirmed their participation.

Götz Paschmann, MPE, Garching, Germany (Team Leader)
Stein Haaland, University Bergen, Norway
Bengt Sonnerup, Dartmouth College, Hanover, NH, USA
Tim Horbury, Imperial College, London, UK
Joachim Vogt, Jacobs University Bremen, Germany
Wai-Leong Teh, LASP, Boulder, CO, USA.

The team has been kept intentionally small, in order to assure that the focus is maintained and the work is efficient. Each member has been selected for his specific contributions and skills. *Goetz Paschmann* and *Stein Haaland* have prepared the data base for the study, by having performed MVA and deHoffmann-Teller/Walén analysis, and some preliminary assessment of the accuracy of the four-spacecraft timing on the set of crossings provided by Knetter. Those results are conveniently compiled in a large spreadsheet. *Bengt Sonnerup* is the inventor of the MHD reconstruction technique, also described in SR-008. It will be a main tool to look at the internal structure of the DDs, but it requires experience and has to be used with extreme care. *Tim Horbury* is an expert on solar wind discontinuities, having published important papers on the subject, including a chapter on multi-spacecraft turbulence analysis in SR-008. *Joachim Vogt* has developed a four-point wave analysis method (the wave surveyor technique) that we intend to apply to the Alfvénic fluctuations surrounding the DDs, and he recently presented a methodological framework to generalize some of the established four-point methods to the case of three spacecraft. As organizer of several workshops he has demonstrated his expertise in advanced time-series analysis techniques, with special emphasis on multi-point measurements. *Wai-Leong Teh* has designed the numerical code for MHD reconstruction (as well as for Grad-Shafranov-based and Hall MHD- based reconstruction) and will be responsible for providing results of the technique at the meetings. As the comparison and, possibly, further development of some of the tools are necessary, its is important that all team members are experts on state-of-the-art methodological issues. Evidence of their expertise is that all have been authors of chapters in ISSI's recent SR-008 "Multi-Spacecraft Analysis Methods Revisited".

While several team members' experience with DDs is based primarily on their fundamental contributions to the clarification of the nature (TD vs. RD) of Earth's magnetopause, much of this expertise directly applies to solar wind DDs as well. Nevertheless, we might want to add *Marcia Neugebauer*, Tucson, USA, and/or *Jack Gosling*, Boulder, USA, who both have been deeply involved in studies of solar wind discontinuities. Given the emphasis on methodological issues at the first meeting, their participation in that meeting would not seem necessary, and we have not yet contacted them.

Agenda for first team meeting In preparation of the first meeting, we will produce a spreadsheet that contains, for all events, the information that we have already obtained, such as the normal directions and normal components from single- and four-spacecraft techniques, the results of the Walén-relation tests, the magnetic shear across the DDs, the solar wind speed, the pitch-angles of the 'Strahl' electrons that mark the direction away from the sun, and others. This will allow us to quickly filter the list for certain properties or combinations thereof.

At the first meeting we will start with presentations of the data set and what we already know about it, followed by presentations of the various techniques that we have already applied or which team-members propose to apply. It is anticipated that the discussion will lead to modified approaches and their application to selected test cases, which should clarify how to proceed. The end result should be a step-by-step procedure to be applied to the complete data set or suitable subsets thereof, with results to be available before the second meeting.

Schedule The current plan is for two 5-day meetings, one in the Fall of 2009, the second in Spring 2010.

Facilities required Team members will bring their own laptops, except that Bengt Sonnerup will need access to an Apple Mac. In preparation for the first team meeting, entire subsets of the events will have been analyzed using several of the methods described above, and the results stored on hard-disks. In case other Cluster events are to be added, this will be easy, since the standard Cluster data are online and accessible via internet. The high-resolution magnetic field data are not on line as a rule, but have been processed for a subset of events already and are accessible via Internet as well. As to rooms, it would be good if, in addition to the main meeting room on the 3rd floor, a second smaller room were available.

Financial support The team would be happy with the standard arrangements, except that we would like to switch the travel support from the team leader to Professor Sonnerup, who is now retired and no longer has a NASA grant to support his travels to ISSI.

Appendix 1

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Appendix 2: Figures

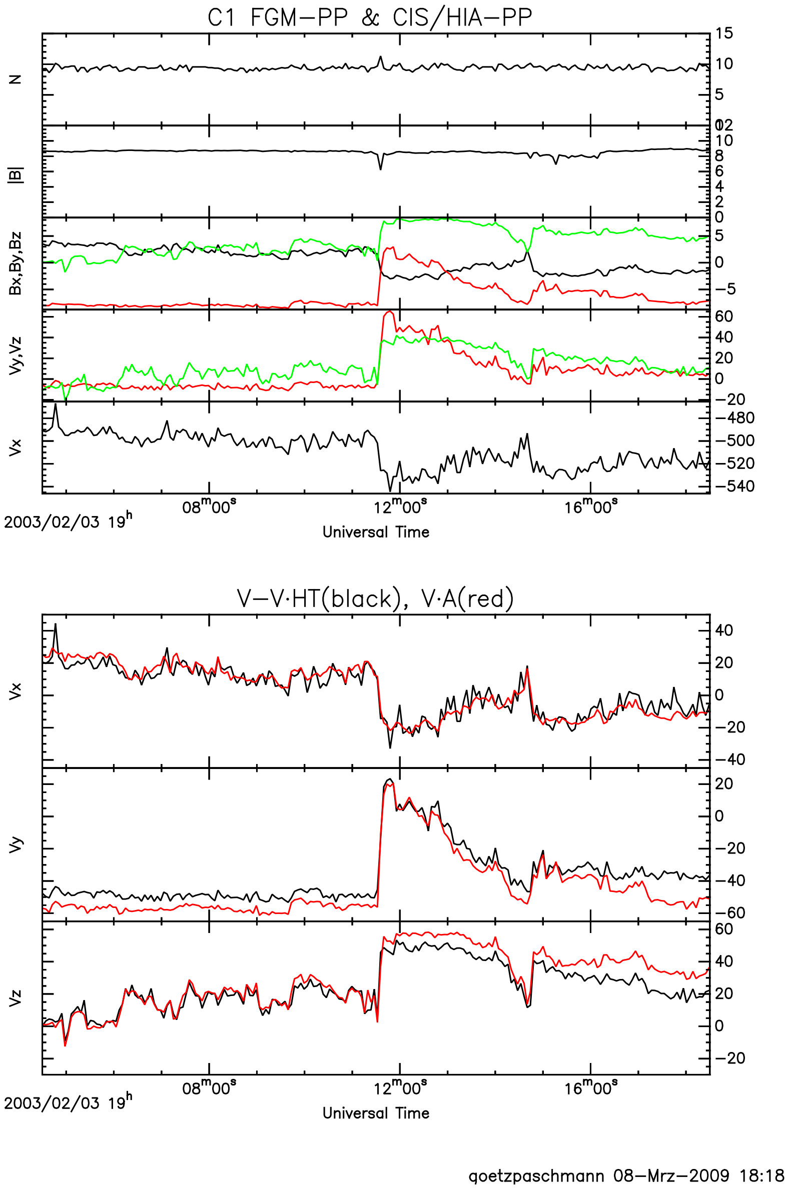
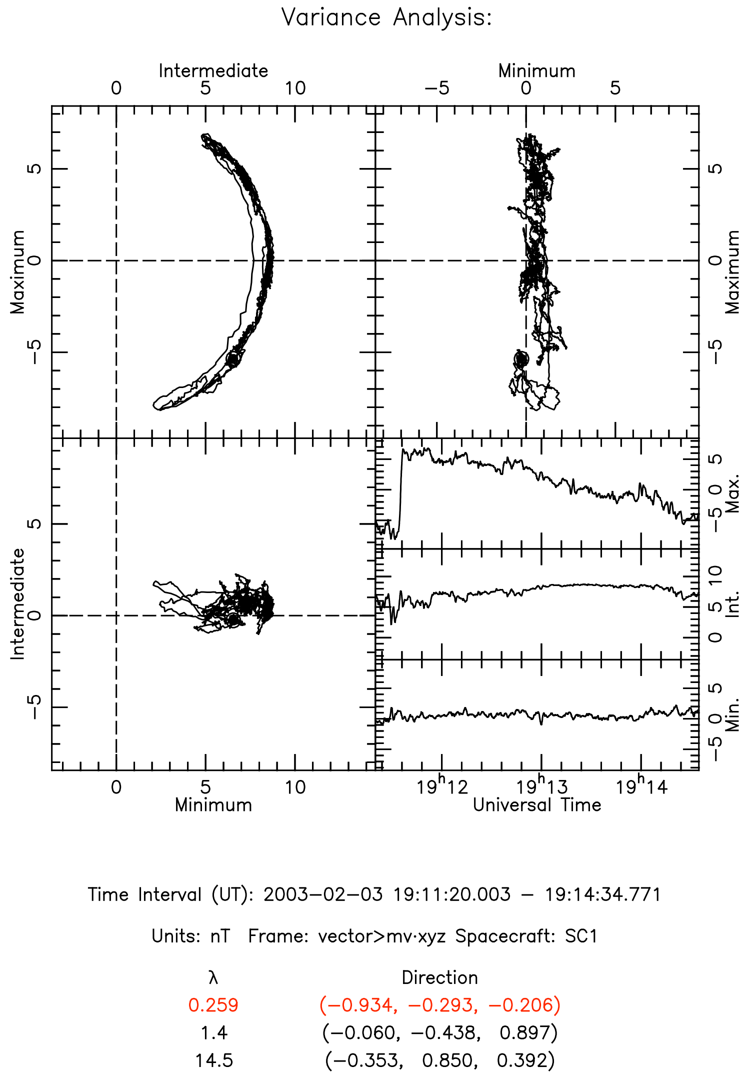


Figure 1: Example of a solar wind discontinuity embedded in Alfvénic fluctuations. The top five panels show the plasma density N (cm^{-3}), the magnitude $|B|$ and components, B_x, B_y, B_z, of the magnetic field (nT), and the components, V_x, V_y, V_z, of the plasma velocity (km s^{-1}), with V_x shown in a separate panel because of its large magnitude. The x, y, and z components are color coded as black, red, and green, respectively. The bottom three panels show the result of the Walén test, in terms of the velocities transformed into the deHoffmann-Teller frame (black) and the Alfvén velocities (in red). The good agreement identifies the fluctuations as Alfvénic.



Time Interval (UT): 2003−02−03 19:11:20.003 − 19:14:34.771

Units: nT Frame: vector>mv·xyz Spacecraft: SC1

λ	Direction
0.259	(−0.934, −0.293, −0.206)
1.4	(−0.060, −0.438, 0.897)
14.5	(−0.353, 0.850, 0.392)

Figure 2: Example of an ‘arc-polarized’ structure, identified by minimum variance analysis (MVA) of the event shown in Figure 1. The hodogram at the top left shows the motion of the magnetic field vector in the plane of the disontinuity, and illustrates the fast rotation of the field within the discontinuity and its subsequent slow return to the initial orientation. The eigenvectors and associated eigenvalues from MVA are shown at the bottom, with the numbers in red marking the implied normal direction.

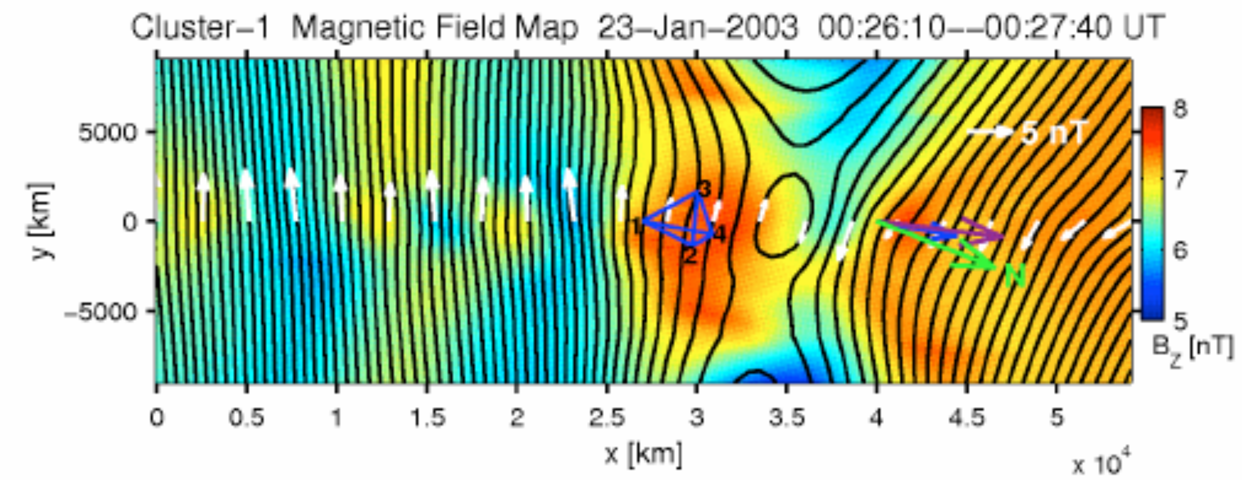


Figure 3: MHD-based reconstruction of a directional discontinuity in the solar wind, seen by the Cluster spacecraft (C1-C4). The map is based on plasma and field data from C1. Black curves are field lines, with the measured field components in the reconstruction (xy) plane shown as white arrows at points along the C1 trajectory (located at $y = 0$). Map colors represent the axial (z) component of the field. Predicted normal vectors, N, are as follows: The green arrow is from timing analysis (its angle to the z-axis is 89°); red arrow (angle = 86°) is from minimum variance analysis (MVA) of the magnetic field, using the constraint $< B_n >= 0$; blue arrow (angle = 140°) is from MVA without constraint. The latter vector appears short because of its large component along the negative z-axis. The Cluster tetrahedron, moving from left to right across the map, illustrates that the spacecraft separation is comparable to, or smaller than, the structures within the discontinuity. Field components predicted from the C1 map at the locations of the other three spacecraft have a correlation coefficient cc = 0.992 with the corresponding, actually measured components; the discrepancy is caused mainly by temporal evolution occurring in the 7 s interval between the first (C4) and the last (C1) crossing.

Appendix 3: Addresses and affiliations of team members

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Appendix 4: CVs of team members

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1971: PhD in Physics, Technische Universität München (R. Lüst)

Positions:
1968 - 1970: Visiting Scientist, Lockheed Palo Alto Research Laboratory
1971 - 1978: Staff, Max-Planck-Institut für extraterrestrische Physik (MPE), Garching, Germany
1978 Visiting Scientist, Los Alamos Scientific Laboratory
1978 - 2004: Senior Scientist at MPE
1999 - 2005, Director, International Space Science Institute, Bern, Switzerland
2004 - present: guest scientist at MPE

Professional recognition:
Fellow, Americam Geophysiical Union;
Fellow, Royal Astronomical Society;
Dr. h.c., Ludwig-Maximilians-Universität München
Principal Investigator on ISEE-2, AMPTE-IRM, Freja, Equator-S, and Cluster

Participation in earlier ISSI activities:
1996-1998: author and editor, ISSI SR-001 (Analysis Methods for Multi-Spaceraft Data);
1996-1999: author and editor, SSSI 6 (Magnetospheric Plasma Sources and Losses);
1999-2002: author and editor, SSSI 15 (Auroral Plasma Physics);
2003-2005: author and editor, SSSI 20 (Outer Magnetospheric Boundaries: Cluster Results);
2004-2007: author, ISSI SR-007 (Calibration of Particle Instruments in Space Physics);
2007-2008: author and editor, ISSI SR-008 (Multi-Spacecraft Analysis Methods Revisited).

Recent Publications:
Paschmann, G.: Recent in-situ observations of magnetic reconnection in near-Earth space, Geophys. Res. Lett. 35, doi = 10.1029/2008GL035297, 2008.

Paschmann, G. and B. U. Ö. Sonnerup: Proper frame determination and Walen test, in "Multi-Spacecraft Analysis Methods Revisited", eds: G. Paschmann & P. Daly, ISSI SR-008, 2008

Sonnerup, B. U. Ö., S. Haaland, S. and G. Paschmann: Discontinuity Orientation, Motion and Thickness, in "Multi-Spacecraft Analysis Methods Revisited", eds: G. Paschmann & P. Daly, ISSI-SR-008, 2008

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Education:
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1992 B.Sc., Instrumentation, University of Bergen Norway.

Employment:
2008 - present: Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany
Cluster mission,
2005 - present: University of Bergen, Norway:
Associate professor in space physics; Teaching, student supervision.
2004 - present: University of Oslo, Norway:
Lecturing, FYS5610 - Space physics course for Master and Ph.D students.
2001 - 2007 Max-Planck-Institute for extraterrestrial Physics, Garching, Germany
Analysis of Cluster data.
1999 - 2003 International Space Science Institute, Switzerland: Post Doc position.
Involved in various science projects, such as application/development of advanced methods
in space data interpretation, auroral physics, X-ray image processing and analysis.

Participation in earlier ISSI activities:
1999 - 2002: contributions to SSSI 15 (Auroral Plasma Physics) as author and editor;
2003 - 2005: contributions to SSSI 20 (Outer Magnetospheric Boundaries) as author and editor;
2008: contribution to ISSI SR-008 (Multi-Spacecraft Analysis Methods Revisited).
Member of ISSI Team 91, "Trancient processes in the magnetotail" .

Relevant recent publications:
Sonnerup, B. Haaland, S. and Paschmann, G.: "Discontinuity Orientation, Motion and Thickness"
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Orientation and Motion of a Plasma Discontinuity from Single-spacecraft Measurements:
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Minimum Variance of Current Density, Geophys. Res. Lett., 31, L10804, doi:10.1029/2004GL020001, 2004

Haaland, S., B. Sonnerup, M. Dunlop, A. Balogh, E. Georgescu, H. Hasegawa, B. Klecker,
G. Paschmann, P. Puhl-Quinn, H. Reme, H. Vaith, A. Vaivads
Four-Spacecraft Determination of Magnetopause Orientation, Motion and Thickness:
Comparison with Results from Single-Spacecraft Methods, Ann. Geophys., 22, 1347, 2004

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1995: PhD in Physics, Imperial College London

Positions:
1995-1998: Postdoctoral Fellow, Imperial College London
1998-2000: Postdoctoral researcher, Queen Mary University of London
2000-2005: Advanced Fellow, Imperial College London
2005-present: Lecturer, Imperial College London
Professional recognition:
European Geophysical Union, Young Talents in Geophysics, 2005
Royal Astronomical Society Fowler Award for Geophysics, 2004
Royal Astronomical Society Blackwell Prize for best geophysical thesis, 1996

Mission involvement:
ESA Guest Investigator, Ulysses. Co-I Investigator, Cluster MAG, DoubleStar MAG, Bepi-Colombo MAG.

Participation in earlier ISSI activities:
Member of several teams (Turbulence 2003, HFAs 2004, Shocks 2007), participant in several workshops (CIRs 1998, Magnetospheric boundaries 2003, CMEs 2004). Contributor to 3 ISSI books (CIRs, CMEs, Multi-spacecraft analysis methods revisited).

Selected recent publications:
Horbury, TS, Forman, M, Oughton, S,
Anisotropic Scaling of Magnetohydrodynamic Turbulence,
Phys. Rev. Lett., 101, ISSN: 0031-9007, 2008

Horbury, TS, Osman KT, Multi-Spacecraft Turbulence Analysis Methods,
In: G. Paschmann and P. W. Daly, editors, Multi-Spacecraft Analysis
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correlation functions in solar wind turbulence,
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of interplanetary southward magnetic field turnings,
J. Geophys. Res. 106, 30001 - 30009, 2001

Horbury, TS, Burgess, D, Franz, M, et al , Three spacecraft observations of solar
wind discontinuities, Geophys. Res. Lett. 28, Pages: 677 - 680, 2001.

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Participation in earlier ISSI activities:
Author or co-author Chapters 8 and 9 of SR-001; Chapters 1, 7, and 9 of SR-008;
Chapters 8 and 10 of Space Sciences Series, SSSI Volume 20;
Participant in two additional ISSI teams (Dunlop and Nakamura);
Extended stays at ISSI in 2001- 2002, with support from the A. v. Humboldt Foundation.

Honors:
Fellow, American Geophys. Union, 1989;
A. v. Humboldt Prize, 2000

Selected Relevant Publications:
Hu, Q. and B.U.Ö. Sonnerup, Reconstruction of magnetic clouds in the solar wind: Orientations and configurations, J. Geophys. Res., 107, No. A7, 10.1029/2001 JA000293, 2002.

Sonnerup, B. U. Ö., H. Hasegawa, and G. Paschmann, Anatomy of a flux transfer event seen by Cluster, Geophys. Res. Lett., 31, L11803, doi:10.1029/2004GL020134, 2004
.
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Sonnerup, B. U. Ö., and W.-L. Teh, Reconstruction of two-dimensional coherent structures in ideal and resistive Hall MHD: The theory, J. Geophys. Res., 114, in press, doi:10.1029/2008JA013897, 2009.

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2. Magnetopause structures and FTEs.
3. Kelvin-Helmholtz wave vortices at the magnetopause flank.

Recent Publications:
Sonnerup, B. U. Ö. and W.-L. Teh,
Reconstruction of two-dimensional coherent MHD structures in a space plasma: The theory,
J. Geophys. Res., 113, A05202, 2008.

Teh, W.-L. and B. U. Ö. Sonnerup,
First results from 2D MHD reconstruction: Magnetopause reconnection event seen by by Cluster,
Ann. Geophys., 26, 2673-2684, 2008.

Teh, W.-L., B. U. Ö. Sonnerup, Q. Hu, and C. F. Farrugia,
Reconstruction of large-scale reconnection exhaust structure in the solar wind,
Ann. Geophys., 27, 1-16, 2009.

Eriksson, S., H. Hasegawa, W.-L. Teh, B. U. Ö. Sonnerup, J. P. McFadden, K.-H. Glassmeier,
Roux, V. Angelopoulos , C. M. Cully, and R. E. Ergun,
Magnetic island formation between large-scale flow vortices at an undulating
postnoon magnetopause for northward IMF,
J. Geophys. Res., 114, A00C17, 2009.

Sonnerup B. U. Ö. and W.-L. Teh,
Reconstruction of two-dimensional coherent structures in ideal and resistive Hall MHD: The theory,
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Positions:
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1997-1998: Head of the Auroral Imaging Team, MPE Garching, Germany
1999-2001: Wissenschaftlicher Assistent (equiv. Assistant Professor), Institut für Geophysik und Meteorologie, Technische Universität Braunschweig, Germany
2001-present: Associate Professor of Physics, Jacobs University Bremen (JUB), Germany
2005-2007: Director, Computational Laboratory for Analysis, Modeling, and Visualization, Bremen.

Professional recognition:
2202 & 2006, Teaching Award, Jacobs University Bremen
Co-Chair of COSPAR Capacity Building; organizer of two Capacity Building Workshops (Beijing 2004, and Sinaia 2007).
2008-present: Associate Editor, Journal of Geophysical Research, Space Physics.

Participation in earlier ISSI activities:
1996-1998: Author, ISSI SR-001 (Analysis Methods for Multi-Spaceraft Data);
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Relevant recent publications:
Vogt, J., A. Albert, and O. Marghitu (2009),
Analysis of three-spacecraft data using planar reciprocal vectors: methodological framework and spatial gradient estimation,
Ann. Geophys., 26, submitted.

Vogt, J., Y. Narita, and O. D. Constantinescu (2008),
The wave surveyor technique for fast plasma wave detection in multi-spacecraft data,
Ann. Geophys., 26, 1699 - 1710.

Vogt, J., G. Paschmann, and G. Chanteur (2008), Reciprocal vectors,
in "Multi-Spacecraft Analysis Methods Revisited", eds: G. Paschmann & P. Daly,
ISSI-SR-0008.

Glassmeier, K.-H. and 18 co-authors, incl. J. Vogt (2008),
Magnetospheric quasi-static response to the dynamic magnetosheath: A Themis case study,
Geophys. Res. Lett., 35, L17S01.