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Final Technical Report

Summary of Research on Grant NAG5-6658, 1/1/1998 - 6/30/2001
Ulysses Data Analysis: Magnetic Topology of Heliospheric Structures

Research supported by this grant was reported in the following nine publications:

1. Kahler, S. W., Detecting interplanetary CMEs with solar wind heat fluxes, in *Physics of Space Plasmas (1998). Number 15*, edited by T. Chang and J. R. Jasperse, 191-196, MIT Center for Theoretical Geo/Cosmo Plasma Physics, Cambridge, MA, 1998.
2. Kahler, S. W., N. U. Crooker, and J. T. Gosling, A magnetic polarity and chirality analysis of ISEE 3 interplanetary magnetic clouds, *J. Geophys. Res.*, *104*, 9911-9918, 1999.
3. Kahler, S. W., N. U. Crooker, and J. T. Gosling, The polarities and locations of interplanetary coronal mass ejections in large interplanetary magnetic sectors, *J. Geophys. Res.*, *104*, 9919-9924, 1999.
4. Kahler, S. W., N. U., Crooker, and J. T. Gosling, Exploring ISEE 3 magnetic cloud polarities with electron heat flux, in *Solar Wind Nine*, edited by S. Habbal et al., 681-684, Amer. Inst. Phys., New York, 1999.
5. Crooker, N. U., J. T. Gosling, et al., CIR morphology, turbulence, discontinuities, and energetic particles, in *Corotating Interaction Regions, ISSI Space Sci. Ser.*, edited by A. Balogh, J. T. Gosling, J. R. Jokipii, R. Kallenbach, and H. Kunow, pp. 179-220, Kluwer Acad., Dordrecht, 1999. Also, *Space Sci. Rev.*, *89*, 179-220, 1999.
6. Crooker, N. U., S. Shodhan, R. J. Forsyth, M. E. Burton, J. T. Gosling, R. J. Fitzenreiter, and R. P. Lepping, Transient aspects of stream interface signatures, in *Solar Wind Nine*, edited by S. Habbal et al., 597-600, Amer. Inst. Phys., New York, 1999.
7. Burton, M. E., M. Neugebauer, N. U. Crooker, R. von Steiger, and E. J. Smith, Identification of trailing edge solar wind stream interfaces: A comparison of Ulysses plasma and composition measurements, *J. Geophys. Res.*, *104*, 9925-9932, 1999.
8. Crooker, N. U., S. W. Kahler, J. T. Gosling, D. E. Larson, R. P. Lepping, E. J. Smith, and J. De Keyser, Scales of heliospheric current sheet coherence between 1 and 5 AU, *J. Geophys. Res.*, *106*, 15,963-15,971, 2001.
9. Crooker, N. U., J. T. Gosling, and S. W. Kahler, Reducing heliospheric magnetic flux from CMEs without disconnection, *J. Geophys. Res.*, in press, 2001.

Research reported in Papers 1, 2, 3, and 4 reflects the continuation and completion of our studies using ISEE 3 data, begun with support from a previous grant. These papers lay the groundwork for using suprathermal electron data as a tool to probe the topology of magnetic structures in the heliosphere and to understand the relationship between them. They focus on magnetic clouds, which come from coronal mass ejections (CMEs) on the Sun, and on the heliospheric current sheet (HCS), which divides the heliosphere into two hemispheres of opposite magnetic polarity. Specific results are listed at the end of this report.

Paper 5 is a review representing the culmination of a series of three workshops on another heliospheric structure, the corotating interaction region (CIR). CIRs develop as high-speed streams of solar wind overtake slower ones. Paper 6 reports on a surprising result from an analysis of CIRs using the electron data tool: What is usually treated as a steady-state signature of the interface between fast and slow flow can sometimes occur in transient material from CMEs.

Paper 7 resulted from a collaboration with colleague Marcia Burton at the Jet Propulsion Laboratory. Ulysses data were used to show for the first time that the entropy signature traditionally used to identify the interface marking passage from slow to fast flow on the leading edge of a high-speed stream, that is, in a CIR, can also be used to identify the interface marking passage from fast to slow flow on the trailing edge.

Papers 8 and 9 report on recent research, which we describe here in more detail and illustrate with figures. Paper 8 draws on data from a period of near-radial alignment between Wind at 1 AU and Ulysses at 5 AU. It uses the suprathermal electron tool to compare HCS crossings and reports on three significant findings. First, contrary to what is normally found, there is a major mismatch between the HCS crossings predicted by the corresponding coronal field source surface map and those observed at 1 AU. The mismatch is ascribed to the rapidly changing configuration of the coronal fields during this period, which was in the ascending phase of the solar cycle. The solar wind flow was characterized by small-scale, nonrecurrent streams, many containing intervals of counterstreaming electrons indicating a transient source. The nature of the solar wind at this time makes the second finding all the more remarkable: Whereas ballistic mapping between Wind and Ulysses proved useless for tracking HCS crossings, mapping with a 1-D hydrodynamic simulation gave coherent results. The compressing and stretching of the distances between these markers by the small-scale streams is well-represented by the 1-D code, and the result implies large-scale coherence for the HCS. Finally, the third and most significant finding is that the local structure of the HCS at Wind at each of the four crossings closest to radial alignment did not match that at Ulysses. The results are consistent with the view that at the local level, the HCS is a layer of intertwined flux ropes and tubes rather than a simple sheet.

This complex view of local HCS structure is illustrated schematically in Figure 1. It shows a cross-section of a small portion of the HCS in the form of a network of flux tubes of mixed magnetic polarities. Some of the tubes may locally turn back on themselves (a feature easily detected with the electron tool), in which case their true polarities would oppose the illustrated magnetic polarities. The small arrows in the regions bounding the flux tubes indicate current flow. Together these constitute the total current in the HCS, flowing predominantly from left to right, consistent with the global polarity pattern. The lines labeled *a-d* in Figure 1 are examples of spacecraft trajectories across the structure for a variety of HCS orientations. They attempt to synthesize a number of competing ideas about HCS structure. Line *a* represents the ideal crossing through a single current sheet with no structure on either side, characteristic of none of the crossings analyzed in Paper 8. Lines *b* and *c* represent crossings with multiple magnetic polarity reversals. They could be either true multiple polarity reversals or one true reversal mixed with local reversals, depending upon whether or not fields turn back on themselves. While in isolation the signature along line *b* could be interpreted as passage through parallel multiple sheets extending from multiple helmet structure on the Sun, and the signature along line *c* could be interpreted as passage through a wavy current sheet, the structure as a whole is neither of those. Line *d* represents passage through a single flux tube or, if the current were distributed across it, a flux rope, as observed on the fourth crossing by the Wind spacecraft.

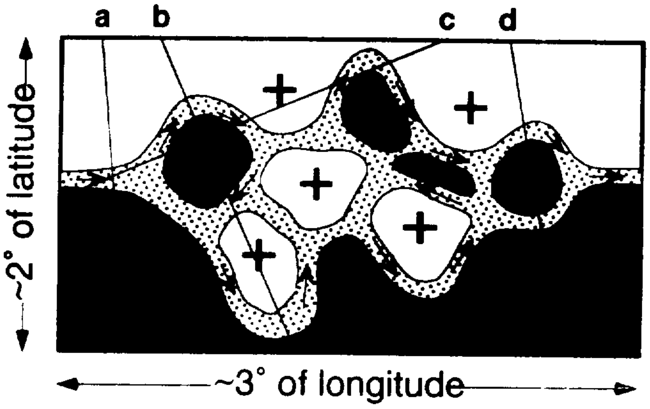

Figure 1. Schematic drawing of a cross-section of the HCS illustrating local structure. Flux tubes and ropes of opposite polarity meet and intertwine. Current in the HCS flows primarily around the boundaries of these tubes, as indicated by the arrows. The lines marked *a-d* illustrate hypothetical trajectories through the structure, which will produce a variety of signatures (from Paper 8].

Paper 9 addresses the global issue of the heliospheric magnetic flux budget. Ever since CMEs were discovered and understood to be magnetically closed, that is, magnetic field lines threading through them tend to have both ends rooted in the Sun, the question of what balances the magnetic flux they contribute to the heliosphere has been debated. Until 1995, disconnection, illustrated in Figure 2a, was thought to be the only viable way to reduce flux, yet evidence of disconnection in the solar wind is much too sparse to provide a balance. Paper 9 traces the development of an alternative process illustrated in Figure 2b, which we call "interchange reconnection." The paper suggests that interchange reconnection occurs in the leg of a CME until it is completely open, long after its leading edge has departed from the vicinity of the Sun, and discusses preliminary findings from Ulysses testing that view.

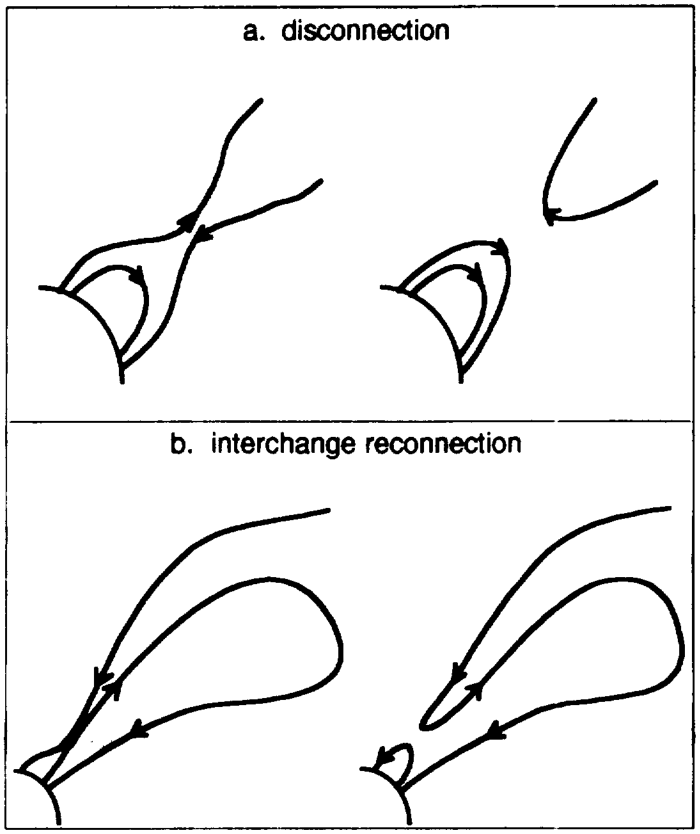

Figure 2. Modes of reconnection for reducing magnetic flux in the heliosphere: a.) merging of two open field lines at the apex of a helmet streamer, which releases a U-shaped field line; b) an open field line merging with a closed field line in one leg of a CME loop which has already expanded into the heliosphere [adapted from Paper 9].

In summary, the most important, specific results from the research supported by this grant are:

- The closed magnetic fields of magnetic clouds from CMEs usually point in the same direction as their surrounding fields so that clouds tend not to disrupt the large-scale pattern of magnetic sectors in the heliosphere.

- Although magnetic clouds fit models of single flux ropes, the direction of suprathermal electron fluxes within them sometimes indicate changes in polarity suggesting multiple structures.

- What is usually treated as a steady-state signature of the interface between fast and slow flow in the solar wind can sometimes occur in transient material from CMEs.

- The entropy signature traditionally used to identify the interface marking passage from slow to fast flow on the leading edge of a high-speed stream can also be used to identify the interface marking passage from fast to slow flow on the trailing edge.

- Although on a global scale the HCS is a coherent sheet separating magnetic fields of opposite polarity, at the local level it often appears to be a complex layer of intertwined flux ropes and tubes.

- The magnetic flux added to the heliosphere by closed fields from CMEs most likely is returned to the Sun through a process of interchange reconnection in the foot of the CME, which opens the CME fields, rather than through disconnection achieved by merging of open fields elsewhere.

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Dear Dr. Guhathakurta; Zika

Enclosed please find my Final Report on grant NAG5-6658.

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