Progress Report: Radial Evolution of Solar Wind Structure
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Abstract: A key element of successful solar terrestrial predictions is to be able to predict how solar wind structure evolves radially as it propagates from the sun. This effort examines available solar wind data over a variable range of radial separations, examining both stream interactions and interplanetary coronal mass ejections, both to gather empirical understanding of their evolutions and to provide constraints for existing MHD models. The major results in year 1 concerned establishing baseline conditions at 1AU as a function of the phase of the solar cycle. Preparations were also made for the second year's effort exploring the heliocentric radial gradient in the structure and dynamics of the solar wind.

1. Introduction

Successful predictions of space weather depend on our ability to calculate how solar wind structure evolves with radial distance. The majority of our understanding of the structure of the solar wind and interplanetary magnetic field is based on observations at a single heliocentric distance, 1 AU. There are quasi-steady, corotating interaction regions where fast streams overtake slow (Gosling et al., 1978), and a heliospheric current sheet, defined by the interplanetary magnetic field (e.g. Crooker et al., 1993; 2001). There are also transient events, the most notable being the interplanetary coronal mass ejection (e.g. Gosling, 1990). The properties of all these features evolve with heliocentric distance. In the past a paucity of coverage at heliocentric distances other than 1 AU limited our ability to study the radial evolution, either statistically as a function of distance, or by direct comparisons of the same feature at two different distances. Direct comparisons (e.g. Mulligan et al., 2001) are most valuable because the period of shifting radial alignment that naturally arises in such studies could be used to probe longitudinal extent and structure as well as radial evolution. Several long-lived missions in the modern epoch are ideal for such a study. The Cassini spacecraft (Russell, 2002) was launched in 1997 and has spiraled through the solar system reaching 9.5 AU only this summer. Throughout this mission ACE (Russell et al., 1998) solar wind measurements have been available at 1 AU. The Ulysses spacecraft has also been in heliocentric orbit for many years but its high inclination orbit provides fewer conjunctions with the ACE spacecraft. Nevertheless, the available data from near conjunctions need to be examined. An earlier data set with Pioneer Venus at 0.7 AU, and IMP 8 and ISEE 3 at 1 AU will also be explored. These data reside at either UCLA or Los Alamos and are a natural for a UCLA-Los Alamos IGPP collaboration. The conclusions from the study will be used both to improve our empirical understanding of ICMEs and also to provide input to solar wind MHD models that are being used as space weather predictors.

2. Project Objectives

As illustrated in Figure 1, the structure of the heliosphere is set by the solar corona, whose magnetic field is in turn established by the extension of the photospheric field into space.

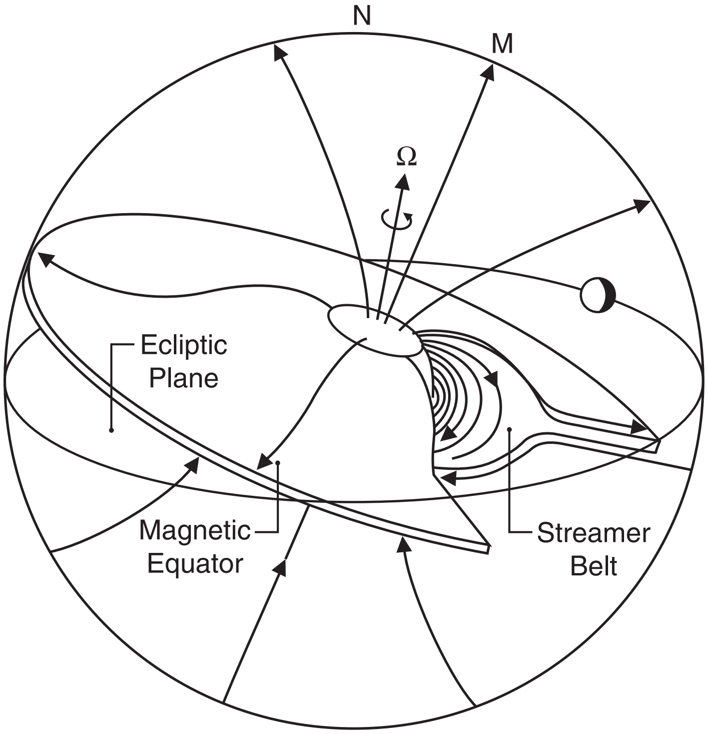

Figure 1. Schematic diagram showing the coronal and heliospheric magnetic field in relation to the ecliptic plane in which the Earth orbits. The magnetic axis of the sun, M, is tilted with respect to the rotation axis, Ω. This tilt allows the fast streams to interact with the slow streams as the sun rotates about Ω. In the course of a year the Earth's orbital motion carries it above and below the rotational equator. If the tilt of the magnetic axis, M, is sufficiently large, the rotation of the Sun carries the solar magnetic equator over the Earth at least twice each solar rotation.

This magnetic structure is not symmetric about the rotational equator. Thus the fast and slow streams can collide with each other as the sun rotates. The pressure waves associated with this collision steepen with radial distance, eventually forming shocks, often a forward and reverse pair, at distances beyond 1 AU as illustrated in Figure 2 (e.g. Hundhausen, 1995). A spatial density structure set in place at the Sun should be in pressure balance with the surrounding magnetic field structure, by the time it reaches 1 AU and any gradients in the combined magnetic and thermal pressures are quite weak. In contrast, the pressure gradient associated with the compressed plasma resulting from the collision of fast and slow streams should be significant and the structure will evolve considerably with heliocentric distance.

Similarly, the heliospheric current sheet, that separates interplanetary space into regions of opposite magnetic polarities, may also have properties set back at the Sun as well as properties that evolve with heliocentric distance. Is there reconnection across the current sheet that proceeds as the solar wind moves outward? Observations of the same feature at two radial distances can provide answers.

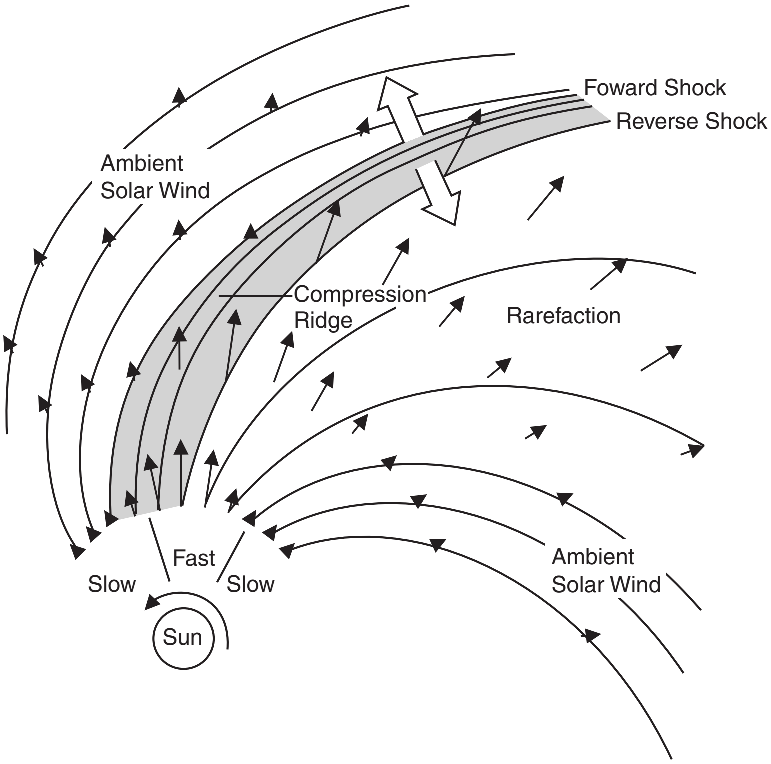

Figure 2. Schematic diagram of solar wind structure in the plane perpendicular to rotation axis of the sun. Because the magnetic structure is tilted with respect to the rotational equator, the fast streams in the rotating solar wind overtake the slow streams. The consequent pressure ridge between the two streams steepens with radial distance, forming a forward and reverse shock pair.

The evolution of solar wind disturbances associated with coronal mass ejections is complex and relatively poorly understood (e.g. Burlaga, 1988). These disturbances should evolve considerably as they move outward from the Sun. Figure 3 shows a twisted magnetic flux tube anchored in the solar corona. Such a structure is the standard paradigm upon which magnetic clouds or interplanetary coronal mass ejections are described. However, they surely are not perfectly cylindrical in cross section, nor can they always be found in a relaxed “Taylor state” which is describable as a Bessel function, and also most commonly used to perform mathematical fits to flux rope ICMEs. Moreover as ICMEs expand and the magnetic structure weakens, we expect the structure of the solar wind speed to distort the magnetic structure in the same way as this velocity structure causes pressure ridges and density and magnetic field pile up at fast-slow stream boundaries. Eventually at some radial distance ICMEs probably do not have a recognizable flux rope structure.

The evolution of quasi-stationary high and low speed streams as a function of distance and latitude and longitude is relatively well understood. Nevertheless there still remains some uncertainty, where not much evolution of the stream structure has occurred, as to how much density/field structure observed within interaction regions is a remnant of the helmet stream belt and how much is due to the later fast-slow stream compression. There is also presently no good understanding of how ICMEs evolve as they propagate out beyond 1 AU.

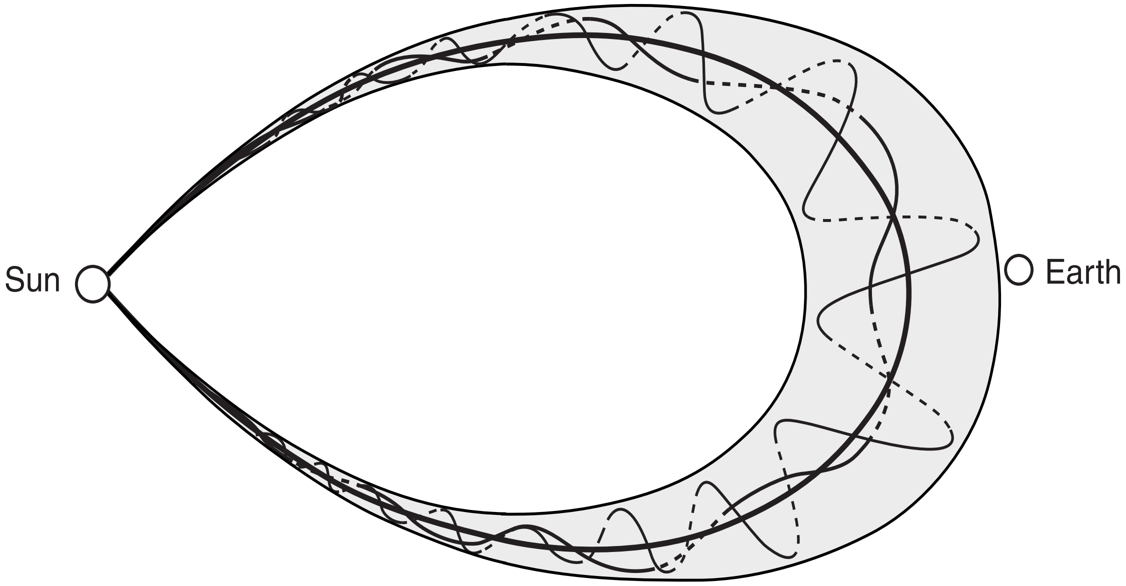

Figure 3. Schematic diagram of magnetic flux rope connected to solar corona. Such a structure accounts for many of the properties of ICMEs observed at 1 AU but must be distorted from this simple shape once the magnetic field weakens as it moves away from the Sun.

It is important to address these questions with the available data now. There is much activity in NASA's Living with a Star program to design missions to enable us to understand and predict space weather. These future programs benefit greatly from syntheses of present understanding and the analyses of presently available data. The investigation outlined herein will help guide the conduct of these future missions.

3. Summary of Results

The first tasks completed when this proposal was funded was to tie up the precursor studies began by undergraduate student Aniketa Shinde and to support the IGPP conference on Sun-Earth Connection Physics. Graduate student, Lan Jian, and then lab Principal Investigator, Jack Gosling, advised on the revisions of the paper that had been prepared on Shinde's results (see 4.1 below). This paper has now been accepted and published in Solar Physics. At the IGPP conference in Merida, C. T. Russell presented an invited review on the effects of the evolving solar wind structure on the Earth's magnetosphere (see 4.2 below). C. T. Russell also presented a contributed paper on Lan Jian's initial results on the use of perpendicular pressure in diagnosing both ICMEs and stream interactions (see 4.3.1 below). This study illustrated that perpendicular pressure was a useful parameter both to measure the strength of ICMEs and SIRs and also to distinguish between the two structures. Only a portion of the solar cycle was examined in this study.

More work was done on the 1AU data and a report made at the Fall AGU meeting (4.3.2). Another quarter of work brought the project to nearly a full solar cycle of coverage and the work reported at the EGU meeting in April. Then the SIR and ICME work was separated into two studies and each phenomenon and its solar cycle behavior characterized separately at the Spring AGU meeting (4.3.4 and 4.3.5). In June 2005, the Solar Wind 11 conference in Whistler had sessions on solar wind heating and ICME behavior and the aspects of the study pertaining to these topics were presented (4.3.6 and 4.3.7). Basically we found irreversible heating when shocks formed.

The solar cycle variation study was completed in June 2005 and the results presented at the SHINE meeting in July (4.3.8 and 4.3.9) on stream interactions and interplanetary coronal mass ejections respectively. Both phenomena have significant changes in strength over the solar cycle. ICMEs vary significantly in occurrence rate also but stream interactions vary only a little in occurrence rate.

After this spate of conferences Lan Jian visited Los Alamos for a month to work with John Steinberg (Jack Gosling having abruptly retired and left LANL) and through John with Ruth Skoug who was on maternity leave. In addition to presenting to them her results thus far, Lan was able to begin preparations for phase two of the work, to examine the Ulysses data in the same way she had examined the 1 AU data that established the baseline variation. As this progress report is being written Lan Jian is writing two papers containing the results of the 1 AU study. An important aspect of these papers are that they contain event lists of all the SIRs and ICME for the past solar cycle with times and quantitative characterizations for their properties at 1 AU. She is also trying to figure out the different properties of SIRs and CIRs (Corotating Interaction Regions).

4. Tangible Results

4.1 Papers in journals

C. T. Russell and A. A. Shinde, On defining interplanetary coronal mass ejections from fluid parameters, Solar Physics, 229, 323-344, DoI/10.1007/s11207-005-8777-x, 2005.

4.2 Invited papers at meetings

4.2.1 C. T. Russell, The Earth’s Magnetosphere, presented at Sun-Earth Connection Physics: The GeoImpact of CMEs, CIRs, and Ordinary Solar Wind, Merida, Mexico, November, 2004.

4.3 Contributed papers at meetings

4.3.1 L. Jian, C. T. Russell, and J. T. Gosling, Using the total perpendicular pressure to diagnose corotating interaction regions and ICMEs, presented at Sun-Earth Connection Physics: The GeoImpact of CMEs, CIRs, and Ordinary Solar Wind, Merida, Mexico, November 2004.

4.3.2 L. Jian, C. T. Russell, and J. T. Gosling, Diagnostics of solar wind processes using the total perpendicular pressure, presented at Fall AGU Meeting, Eos. Trans. AGU, 85(47), Fall Meeting Supl., Abstract SH23A-04, F1491, 2004.

4.3.3 L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann, Characterizing stream interactions and ICMEs using total perpendicular pressure, presented at European Geosciences Union General Assembly, Vienna, April, 2005.

4.3.4 L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann, Using Total Perpendicular Pressure to Diagnose Stream Interactions, presented at Spring AGU Meeting, Eos, Trans. AGU, 86(18), Jt. Assem. Suppl., Abstract SH51A-07, JA459, 2005.

4.3.5 L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann, Identifying and Characterizing ICMEs Using Total Perpendicular Pressure, presented at Spring AGU, 86(18), Jt. Assem. Suppl., Abstract SH53A-11, JA466, 2005.

4.3.6 L. Jian, C. T. Russell, J. T. Gosling and J. G. Luhmann, Measurements of heating at Stream-Stream Interfaces, presented at Solar Wind 11 – SOHO 16, Whistler, British Columbia, June 2005.

4.3.7 L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann, Total pressure signature as a qualitative indicator of the impact parameter during ICME encounters, presented at Solar Wind 11 – SOHO 16, Whistler, British Columbia, June 2005.

4.3.8 L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann, Solar cycle variation of the properties of stream interaction regions (SIRs), presented at the SHINE Workshop 2005, Kona, HI, July, 2005.

4.3.9 L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann, Identifying and distinguishing ICMEs and stream interaction regions (SIRs), presented at the SHINE Workshop 2005, Kona, HI, July 2005.

4.3.10 L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann, Solar cycle variation of the properties of interplanetary coronal mass ejections (ICMEs), presented at the SHINE Workshop 2005, Kona, HI, July 2005.

5. Conclusions

Graduate student Lan Jian has made tremendous progress in her first year of this study examining and characterizing the entire 1 AU database provided by ACE and Wind. This provides an excellent baseline over the solar cycle to use for the radial evolution study. In this study thus far she has overturned a number of existing paradigms. First the stream structure is a very persistent one and not simply a declining phase phenomenon. Certainly though the individual streams last longer in the declining phase. Also shocks do not form simultaneously in the forward and reverse direction, as once believed. Another important practical discovery is that the peak in pressure is generally sharp and can be used to define the stream interface quite precisely. Pressure is also an ideal adjunct in the discrimination of stream interaction and ICMEs. We now anxiously await the results of the comparison with the Ulysses data to see how the solar wind structure evolves with heliocentric distance and latitude.

6. References

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