GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 19, PAGES 2075-2078, SEPTEMBER 15, 1994

Macroscale coherence of the heliospheric current sheet: Pioneers 10 and 11 comparisons

George Siscoe[1] and Devrie Intriligator
Space Plasma Laboratory, Carmel Research Center, Santa Monica, California

Abstract. We use the near radial alignments of Pioneers 10 and 11 during 1974 to study the macroscale geometry of the heliospheric current sheet (HCS). The interval of near alignment gave eight analyzable cases of encounters of both spacecraft with the same HCS and one case in which the IMP and Pioneer 11 spacecraft, while nearly radially aligned, encountered the same current sheet. The degree of macroscale coherence of the HCS was judged by comparing observed solar wind speeds against solar wind speeds calculated on the bases of HCS encounter times and ideal Parker spiral geometry. The correlation coefficient between the two sets of speeds is 0.53. The difference between the calculated and observed speeds can be understood in terms of observed deviations from ideal spiral geometry in the ecliptic plane or in terms of typical corrections to the calculations from small latitudinal factors. One case, however, defies explanation in these terms. This range of behavior demonstrates that the HCS is a useful probe of heliospheric dynamics.

Introduction

The near alignment of Pioneers 10 and 11 for ten months in 1974 when the spacecraft had heliocentric separations between 1 AU and 2 AU radially, 2° to 2.5° latitudinally, and 1° to 10° azimuthally offers an opportunity to document the degree of radial coherence of corotating structures on a large spatial scale. Earlier, using data from a one month interval when earth also aligned with the Pioneers, we documented the coherence from 1 AU to nearly 6 AU of structures associated with corotating interaction regions [*Siscoe and Intriligator*, 1993, hereafter Paper 1]. Here we use the full interval of alignment.

Interest in the geometry of the HCS is high because, as *Suess and Hildner* [1985] note, "the [HCS] can be and has often been used to sort and order solar wind data." It is being used to help infer the latitudinal structure of the interplanetary medium as observed by the Ulysses mission. Studying the HCS geometry is an indirect way to study solar wind flow geometry. *Suess and Hildner* [1985] and *Pizzo* [1994], show how the HCS is warped by large scale inhomogeneities in the solar wind. The present study helps quantify the effects of such macroscale warping. This is complementary to the statistical approach to studying solar wind fluctuations, which has achieved valuable results regarding the universality of such fluctuations using spectral and fractal analyses [*Burlaga*, 1991a,b].

The property of the HCS that we pick to characterize its macroscale geometry is its transit speed between the two spacecraft determined under the assumption that in the ecliptic plane the HCS forms an ideal Parker spiral and out of the plane it forms a surface perpendicular to the plane. By comparing this geometry-dependent speed with the observed solar wind speed, we obtain a measure of the HCS's departure from the idealized surface over a distance scale comparable to the spacecraft separation. Differences in the two speeds can result from deviations from the ideal spiral shape in the ecliptic plane and a non-perpendicular inclination of the HCS to the ecliptic plane.

There are two main results of this study. Given the near alignments of the spacecraft, the disagreements in the speeds are surprisingly large; and nonetheless, in all but one case, typical and actual values of the deviations just noted are qualitatively adequate to account for the differences.

Observations and Comparisons

Most of the heliospheric current sheet (HCS) passages observed by Pioneers 10 and 11 in 1974 lie within the corotating interaction regions (CIRs) of the much-studied two giant streams of 1974 [see refs. in Paper 1]. The streams emanated from polar coronal holes, one in each hemisphere. The HCS approximately bisects the intervening equatorial streamer belt [*Gosling, et al.*, 1981]. About seven recurrences of each stream had stable CIR features that make them candidates for a transit-time study. For the first stream five of these recurrences have no data gaps at either spacecraft at the time of the HCS passage, and can thus be used for determining transit times. The number of usable HCS passages for the second stream is three. To these we add the HCS passages of stream 2 at IMP and Pioneer 11 when these spacecraft were also aligned (Solar Rotation 1929) [Paper 1]. (There was a data gap in Pioneer 10 at the passage of this HCS.) Thus, the present study is based on eight well identified and timed pairs of passages of the HCS at Pioneers 10 and 11 and one pair of aligned passages at IMP and Pioneer 11.

Figure 1 shows the HCS crossing for stream 1 of Bartels Rotation Number 1927. The figure illustrates that the HCS is a good marker for tracking solar wind flow for four reasons: (1) It is unambiguously marked by the 180 degree change in azimuth angle, phi. Though Pioneer 11 records three such changes in phi, the HCS indicated by the vertical line is uniquely identified by its association with the stream interface (SI) at both spacecraft. The SI is marked by an abrupt increase in entropy [*Burlaga*, 1974; Paper 1]. (2) HCS crossings are relatively precisely timed. In this case, the uncertainty in the crossing times is one hour at both spacecraft. For comparison, the transit time is 127 hours. Thus, the relative uncertainty in the transit time is of the order of one percent. (3) The HCS advects with the flow is evidenced by the fact that it maintains its position relative to the SI. Solar wind data at earth for this recurrence of stream 1 also show a virtual coincidence of the HCS and the SI. Thus, they essentially coincided from 1 AU to 5.6 AU. (4) The HCS is a better timing marker than the other discontinuities. The time of passage of the SI at Pioneer 10 is often, as here, not well determined. The forward and reverse shocks are unambiguous and well timed, but they have moved an appreciable distance through the plasma as evidenced by the entropy ramp following the forward shock. (The broad domain of high entropy enveloping the reverse shock is an interesting subject by itself and will be treated separately.)

[1]Also at Center for Space Physics, Boston University, Boston, Massachusetts.

Paper number 94GL01704
0094-8534/94/94GL-01704$03.00

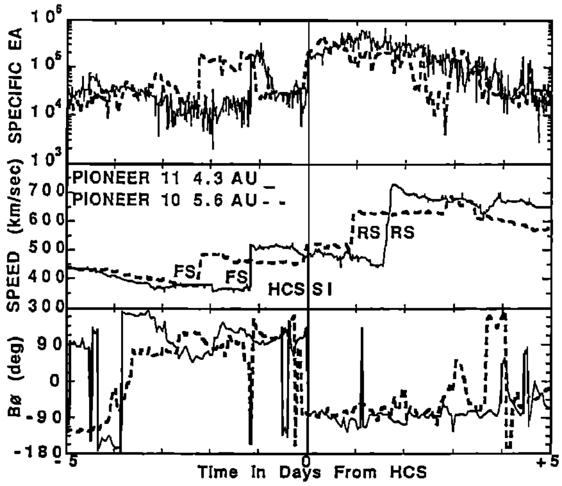

Figure 1. Solar wind specific entropy argument, speed, and interplanetary magnetic field (IMF) direction at Pioneer 10 and Pioneer 11 for ten days centered on the crossing of the heliospheric current sheet in the corotating interaction region of stream 1 of Bartels Solar Rotation 1927. Specific entropy argument is $T/n^{1/2}$, with T in Kelvin and n in ions/cm^3 [*Siscoe and Intriligator*, 1993]. The IMF angle phi is measured counterclockwise from the solar direction. Labeled features are forward shock (FS), heliospheric current sheet and stream interface (HCS & SI), and reverse shock (RS).

Table 1 gives the data needed to determine transit-time speeds and to specify the observed speeds for comparison. A transit-time speed is the speed required for an ideal corotation spiral to pass the points (in inertial space) where the two spacecraft were when the HCS passed them. If the points were strictly radially aligned, one would be concerned simply with radial advection and not with corotation. But as the table shows, the angular separation between the observing points reaches 10°, making corotation corrections important. The operative kinematic formula is $V(\text{corot}) = \Delta R/\Delta T/(1-\Delta\theta/\Omega\Delta T)$, where ΔR is the radial separation of the observation points; $\Delta\theta$ is their angular separation; Ω is the angular velocity of the sun, and ΔT is the transit time.

Specifying the observed comparison speed requires the most appropriate among several relevant speeds: the average speed at Pioneer 10; the average speed at Pioneer 11; the actual speed at the time of the HCS passage at Pioneer 10; the actual speed at the time of the HCS passage at Pioneer 11; or some combination of these. There is no obvious best choice, but fortunately the main point of the comparison is relatively insensitive to the choice. We choose the average of the actual speeds measured at the two spacecraft at the times of the HCS passages. The rationale is that the transit speed is the average of the speed in transit, which if it varies monotonically can be approximated by the average of the speeds at the ends. But there is considerable variation in the speed around the times of the HCS crossings which might reflect a level of turbulence which affects all solar wind parcels, including those advecting the HCS. Thus as a conservative estimate of the uncertainty in specifying observed comparison speed, we take the largest of the one-day standard deviations in speeds at both spacecraft and between both spacecraft.

Figure 2 shows the result of comparing the observed speeds as defined (vertical axis, with their maximum uncertainties) and the transit-time speeds (horizontal axis). Though there is a clear correlation between the observed speeds and the transit-time speeds, there are also large differences between them as evidenced by the displacements of the data points from the diagonal dashed line of equal speeds. In fact the average difference between the speeds, 30.1 km/s, is comparable to the typical inter-rotation variation of the speeds as measured by the standard deviations of the columns of Table 1: 40.2 km/s for observed speeds and 32.0 for transit-time speeds. The relatively

Table 1. Parameters for Computing Transit Time Speeds and for Comparing with Observed Speeds

Rot. # Stream #	TIME (DOY) P 10	P 11	OBSERVED SPEED (km/s) P 10	P 11	ALPHA (deg)	ΔR (10^8 km)	T-T SPEED	DEV (deg)	MEAS DEV
1923(1)-I	71.58	65.203	434.8±8.8	439.8±46.1	0.8	2.387	437	42.4	0.3
1924-I**	122.8	117.58	433.4±16.4	431.4±27.3	2.7	2.097	448	43.5	50.7
1927-I	198.875	193.58	480.1±30.2	497.2±12.1	6.6	1.872	460	-10.5	-5.0
1928-I**	224.00	218.83	503.4±6.0	524.3±15.5	7.7	1.843	410	-15.8	12.8**
1929-I**	251.54	245.705	457.2±20.2	487.4±29.3	9.2	1.842	500	15.3	4.9**
1923(2)-II	107.10	101.95	498.2±7.6	474.5±22.8	2.0	2.166	433	26.7	-23.4
1924-II	134.79	129.08	443.7±8.8	392.3±9.9	3.4	2.048	412	11.7	-36.9**
1925-II	161.62	155.79	424.4±5.5	418.4±25.7	4.7	1.960	480	-5.5	-9.7
	IMP	P 11	IMP	P 11					
1929-II	241.48	255.08	481.1±29.0	526.2±30.0	10.6	5.371	485	-30.3	6.6

Table 1. Column 1 gives the rotations and streams with continuous measurements across the heliospheric current sheet at Pioneers 10 and 11 and at IMP and Pioneer 11 (last row). Columns 2 and 3 give HCS passage times. Columns 4 and 5 give the averages and standard deviations of speeds over one day centered on the HCS passages. Column 6 gives the Pioneer 11 (at HCS passage)-sun-Pioneer 10 (at HCS passage) angles (labeled alpha) measured positive in the sense of solar rotation. Column 7 gives the differences in the heliocentric distances of Pioneer 10 at HCS passage and of Pioneer 11 at HCS passage. Column 8 gives the calculated transit-time speeds. Column 9 gives the deviation from ideal spiral angle needed to make the transit-time speed equal the observed speed. Column 10 gives the observed deviation at Pioneer 10. Rotation number 1923 occurred twice at the Pioneers because Earth was then at solar conjunction 1923(1) means that the rotation began at the Pioneers before it began at Earth (after allowing for radial transit times). 1923(2) is the subsequent rotation. Asterisks in column 1 flag cases in which the uncertainty in specifying the appropriate observed speed exceeds the difference between the observed and transit-time speeds. Asterisks in column 10 flag cases with significant disagreements in deviation angles determined at the two spacecraft.

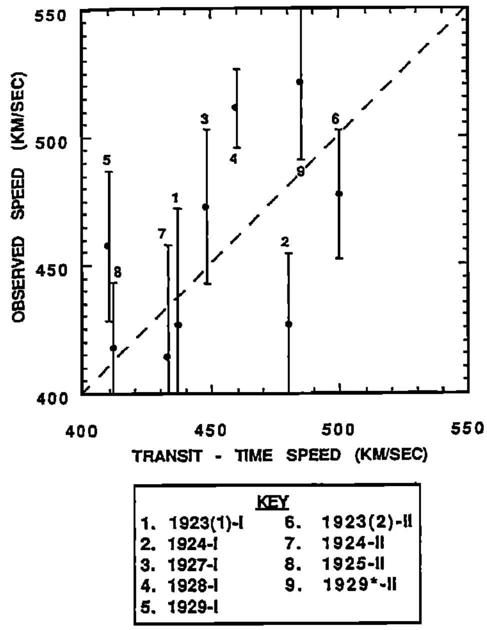

Figure 2. A comparison between observed speeds and speeds calculated from transit times of HCS's under the assumption that HCS's form corotating spirals.

small correlation coefficient between the speed variables, 0.53, makes the same point. If one took advantage of the generous uncertainty estimates to move the values closer to the diagonal, one could increase the correlation coefficient substantially; nonetheless some of the differences lie outside the uncertainty estimates. We therefore regard the relatively large differences between the observed and transit-time speeds to be a real solar wind property.

Despite the low correlation coefficient, the assumption of spiral orientation is much better than the assumption of purely radial orientation, that is, the assumption that the HCS propagates outward like a spherical shell. While no one suggests that the HCS has spherical-shell geometry, this geometry serves as a useful reference against which to compare the assumption of an ideal spiral geometry. This assumption amounts to dropping the $(1-\Delta\theta/\Omega\Delta T)$ term in the kinematic formula. Then the correlation coefficient becomes 0.21, much less than the 0.53 value obtained with the ideal spiral assumption. Another way to express the comparison is in terms of the slope of the linear fit to the V(obs) versus V(cal) scatter plot. A perfect fit would have a slope of 1. The slope in Figure 2 is 0.67. The slope of a spherical-shell model is 0.23. Again HCS geometry proves to be much closer to spiral-like than spherical-shell-like.

The differences between the calculated and observed speeds seen in Figure 2 are not systematic, as might implicate a systematic bias in the measured speeds, for nearly equal numbers of points lie above and below the line of equal speeds. Also the fact that the averages of the two sets of speed variables are nearly identical - 458.2 km/s for observed speed and 451.7 km/s for transit-time speed - argues against a systematic bias in the speed measurements. Thus, we conclude that the differences are real and that they reflect some departure from the assumptions underlying the transit-time calculation: ideal spiral geometry and a "vertical" HCS. We can estimate the magnitudes of the departures needed to make the calculated and observed speeds agree and compare these with typical values and with observed values. For comparison, note that the average difference between the calculated transit-time speed and the observed speeds is about 7% of the average flow speed.

Zonal flows, such as characterize interaction regions, add a factor to the kinematic formula that is percentage-wise equal to the ratio of the zonal flow speed to the corotation speed; this is about 1%. Meridional flows add a factor equal to the ratio of the meridional flow speed to the radial speed times the tangent of the inclination angle of the HCS normal. There is also a factor arising from the latitudinal separation of the spacecraft that equal the sine of the inclination angle times the tangent of the latitudinal separation times the ratio of the solar distance to the spacecraft radial separation. For all nine cases, the HCS is highly inclined; its normal lies on average 17 degrees from the equatorial plane. Thus, the average meridional correction to the kinematic formula is about 2% from the flow effect and about 5% from the separation effect. These factors alone could account for the magnitude of the average difference between the calculated and observed speeds.

Nonetheless, it is instructive to consider in case-by-case detail the possibility that the speed differences result from deviations from the ideal Parker spiral angle. Columns 9 and 10 of Table 1 quantify the requirements. Column 9 gives the angular deviation from ideal spiral (measured positive clockwise) needed to equalize the speeds. Column 10 gives the measured deviation at Pioneer 10 as determined from the vector cross product of the fields on the two sides of the HCS. The double asterisks identify cases in which the determinations at Pioneer 11 and Pioneer 10 differ by more than 30° - a crude quality check.

Consider first the three cases where the spacecraft separation, alpha, is less than 3° (1923(1)-I, 1924-I, and 1923(2)-II). Column nine shows that these cases need large deviations from the spiral direction to equalize speeds. This curious, uniform misbehavior on the part of all three small-angle cases arises mainly because, in calculating the deviation angle, the uncertainties in determining the speed are amplified by at least a factor of 20, which is the reciprocal of 3° in radians. A heuristic interpretation is that, when the spacecraft are so nearly aligned, the modeled HCS must cover a large radial distance in a small azimuthal distance to compensate for a small error in specifying the effective average speed. That these large calculated deviations are spurious can also be seen by the fact that they disagree with measured deviations (column 10) - except for case 1924-I. Here the calculated deviation nearly equals the measured deviation at both spacecraft, implying that the deviation is indeed as large as 40° to 50°. Figure 2 also supports the inference of a large deviation in this case. It shows that among the three small-angle cases only this one has a Parker spiral transit time speed that falls outside the uncertainty bars of the observed speed. (The asterisks in column 1 of the table flag the same fact.) Evidently over the 2.7 degrees of azimuth separating the two spacecraft at this time, the HCS was bent some 40° to 50° away from the spiral orientation, and this bend advected outward 1.3 AU from Pioneer 11 to Pioneer 10.

Consider next the five cases (1927-I, 1928-I, 1929-I, 1924-II, and 1925-II) with alpha greater than 3° excluding the IMP-Pioneer 11 comparison. The calculated deviations for these cases are relatively small, 15° or less compared to 40° or more for the cases with alpha less than 3°. Also for the two cases where the measured deviations are consistent between the two spacecraft (1927-I and 1925-II), the calculated deviations and measured deviations agree to within 5°, which is within the expected uncertainties in determining these numbers. Cases 1928-I and 1929-I (numbers 4 and 5 in Figure 2) show that the calculated deviations, despite their smallness, are sufficient to cause a measurable difference between observed speeds and transit-time speeds. Alternatively, since we cannot confirm the deviations in these cases (as indicated by the asterisks in column 10) the difference in speeds could be attributed to meridional factors from a non-perpendicular HCS. The fifth case (1924-II) adds nothing to the discussion because the disagreement between the observed speed and transit-time speed falls within the uncertainty bars. Even if it did not, the required deviation from ideal spiral is small, and as in the 1928-I and 1929-I cases, this cannot be confirmed by observation.

Finally consider the IMP-Pioneer 11 comparison (case 1929-II, number 9 in Figure 2). The difference between the observed and transit-time speeds lies outside the uncertainty bars. Here alpha is large; hence the calculated requirement on the deviation from the ideal spiral angle (-30.3°) should be serviceably accurate. The measured deviation (6.6°) is also consistent between the two spacecraft (i.e., near alignment with the spiral), and therefore, also should be serviceably accurate. The big disagreement between the calculated and measured deviations at both spacecraft seriously weakens any attempt to explain the difference between the observed and the transit-time speeds in terms of a major warp in the HCS advecting from earth to Pioneer 11. The alternative explanation in terms of a HCS inclination correction is also weakened because the large radial separation in this case gives a latitudinal-separation factor of about 1% instead of 5%. It might be necessary to invoke time dependence; the solar source of the HCS might have moved appreciably in the 17 hours during which it rotated from alignment with IMP to alignment with Pioneer 11. This possibility is faintly supported by the fact that on the following rotation the HCS was disrupted by a series of coronal mass ejections. We must leave the disagreement in this final case as a puzzle that remains to be solved.

Summary and Conclusion

Figure 2 shows that inferences based on the ideal Parker spiral geometry illustrated here by the transit-time speed calculated over about 1 AU of radial distance and 10 degrees of azimuth - can be quite inaccurate. The correlation coefficient between the observed and calculated speeds is only 0.53. Small departures from ideal spiral angle and perpendicular HCS tilt relative to the ecliptic plane significantly degrade the correlation. Our set of nine analyzable rotations contains the following variety of cases: two examples of large inaccuracies in calculated deviations from the spiral angle caused by uncertainties at small azimuthal separation in determining the appropriate solar wind speed; one real case of a large deviation from the ideal spiral angle causing a significant difference between observed and calculated solar wind speeds; two other such significant differences caused by small deviations from the ideal spiral angle, two demonstrably well behaved cases, one apparently well behaved case, and one significantly deviant case with no apparent cause. This observed range of behavior - from order to disorder - makes the HCS a useful probe of macroscale heliospheric dynamics.

Acknowledgments. We thank the referees for noting that meridional factors can significantly affect the transit-time speed. We are indebted to the Pioneer Project Office for the continued success of the Pioneer 10 and 11 missions. We are grateful to Aaron Barnes, Edward J. Smith, and the NSSDC for supplying data used in this study. This work was supported by NASA Ames Research Center under NAS2-13692 and by Carmel Research Center.

References

Burlaga, L.F., Interplanetary stream interfaces, *J. Geophys. Res.*, *79*, 3717-3725, 1974.

Burlaga, L.F., Multifractal structure of speed fluctuations in recurrent streams at 1 AU and near 6 AU, *Geophys. Res. Lett.*, *18*, 1651-1654, 1991a.

Burlaga, L.F., Intermittent turbulence in the solar wind, *J. Geophys. Res.*, *96*, 5847-5851, 1991b.

Gosling, J.T., G. Borini, J.R. Asbridge, S.J. Bame, W.C. Feldman, and R.T. Hansen, Coronal streamers in the solar wind at 1 AU, *J. Geophys. Res.*, *86*, 5438-5448, 1981.

Pizzo, V.J., Global, quasi-steady dynamics of the distant solar wind. 2. Deformation of the heliospheric current sheet, *J. Geophys. Res.*, *99*, 4185-4191, 1994.

Siscoe G., and D. Intriligator, Three views of two giant streams: Aligned observations at 1 AU, 4.6 AU, and 5.9 AU, *Geophys. Res. Lett.*, *20*, 2267-2270, 1993.

Suess, S. T., and E. Hildner, Deformation of the heliospheric current sheet, *J. Geophys. Res.*, *90*, 9461-9468, 1985.

D. S. Intriligator, and G.L. Siscoe, Carmel Research Center, Post Office Box 1732, Santa Monica, CA 90406. (e-mail: dsintriligator@nasamail.nasa.gov)

(Received December 20, 1993; revised May 17, 1994; accepted June 23, 1994.)