Ann. Geophys., 27, 3805–3809, 2009
www.ann-geophys.net/27/3805/2009/

Annales Geophysicae

In situ observations from STEREO/PLASTIC: a test for L5 space weather monitors

K. D. C. Simunac[1], L. M. Kistler[1,2], A. B. Galvin[1,2], M. A. Popecki[1], and C. J. Farrugia[1]

[1]University of New Hampshire, Space Science Center, Durham, NH 03824, USA
[2]University of New Hampshire, Department of Physics, Durham, NH 03824, USA

Received: 29 May 2009 – Revised: 21 September 2009 – Accepted: 26 September 2009 – Published: 7 October 2009

Abstract. Stream interaction regions (SIRs) that corotate with the Sun (corotating interaction regions, or CIRs) are known to cause recurrent geomagnetic storms. The Earth's L5 Lagrange point, separated from the Earth by 60 degrees in heliographic longitude, is a logical location for a solar wind monitor – nearly all SIRs/CIRs will be observed at L5 several days prior to their arrival at Earth. Because the Sun's heliographic equator is tilted about 7 degrees with respect to the ecliptic plane, the separation in heliographic latitude between L5 and Earth can be more than 5 degrees. In July 2008, during the period of minimal solar activity at the end of solar cycle 23, the two STEREO observatories were separated by about 60 degrees in longitude and more than 4 degrees in heliographic latitude. This time period affords a timely test for the practical application of a solar wind monitor at L5. We compare in situ observations from PLASTIC/AHEAD and PLASTIC/BEHIND, and report on how well the BEHIND data can be used as a forecasting tool for in situ conditions at the AHEAD spacecraft with the assumptions of ideal corotation and minimal source evolution. Preliminary results show the bulk proton parameters (density and bulk speed) are not in quantitative agreement from one observatory to the next, but the qualitative profiles are similar.

Keywords. Interplanetary physics (Solar wind plasma) – Ionosphere (Modeling and forecasting)

1 Introduction

Space weather prediction is becoming increasingly important as people rely more and more on technology. Transient events such as coronal mass ejections and solar flares are not the only causes of space weather. Corotating solar wind structures such as stream interaction regions (SIRs) are known to cause recurrent geomagnetic storms (Zhang et al., 2008; Tsurutani et al., 2006). The flux of relativistic electrons at geostationary orbit has also been correlated with the trailing edges of high-speed streams (Baker et al., 1990; Li et al. 2001). By placing a solar wind monitor at the L5 Lagrange point of the Sun-Earth system, nearly all corotating solar wind streams can be observed in situ 3 to 5 days prior to their arrival at Earth. An L5 solar wind monitor has been proposed by groups including Akioka et al. (2005) and Webb et al. (2009).

The heliographic longitude separation between Earth and L5 is 60 degrees. Because the Sun's heliographic equator is tilted about 7 degrees with respect to the ecliptic plane, the separation in heliographic latitude between L5 and Earth can be more than 5 degrees. This relatively small latitude separation is potentially enough to result in substantially different stream structures at the two points of observation (Schwenn, 1990; Leske et al., 2008; Mason et al., 2009; Simunac et al., 2009). Simunac et al. (2009) compared the expected and observed time delay between the observations of stream interfaces on STEREO/B and STEREO/A over heliographic longitude separations ranging from 2 to 48 degrees. They found significant deviations from the expected time-of-arrival when the spacecraft were separated by more than 20 degrees of longitude. Figure 1 shows that NASA's Solar Terrestrial Relations Observatory (STEREO) satellites were separated by about 60 degrees in longitude and more than 4 degrees in heliographic latitude during the month of July 2008. This time period is a logical test for the practical application of a solar wind monitor at L5.

2 Data and observations

The data used in this study are from the Plasma and Suprathermal Ion Composition (PLASTIC) investigation

Correspondence to: K. D. C. Simunac
(k.simunac@unh.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

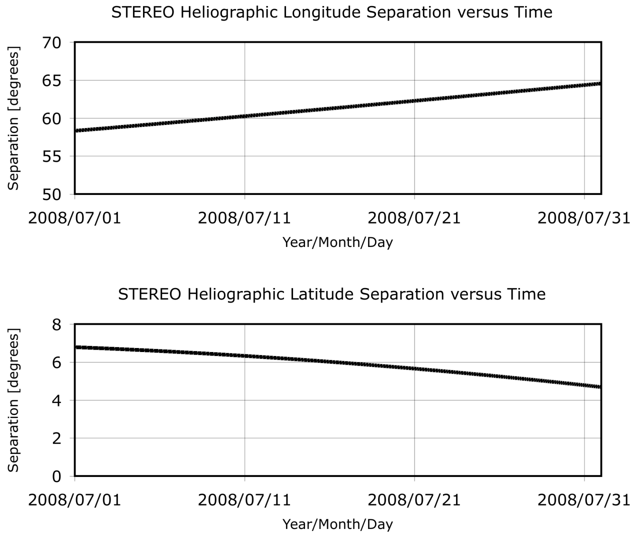

Fig. 1. The STEREO observatories' separation versus time in heliographic longitude (top) and latitude (bottom).

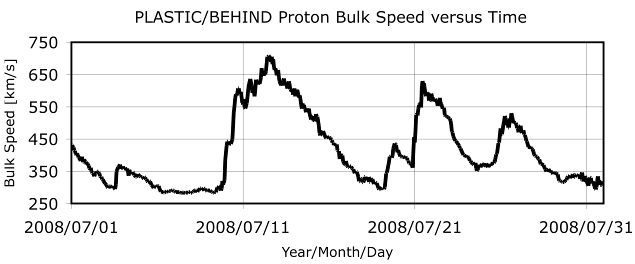

Fig. 2. Solar wind bulk speed measured by PLASTIC/BEHIND in July 2008.

aboard STEREO. PLASTIC is a time-of-flight mass spectrometer that samples ions with energy per charge between 0.3 keV/e and 86 keV/e. For an extensive description of PLASTIC see Galvin et al. 2008. Solar wind proton parameters including bulk speed, density, kinetic temperature, and flow angle are available with one-minute time cadence. For this study the data were averaged over one-hour intervals.

Figure 2 is a plot of solar wind speed observed by PLASTIC/BEHIND versus time. There are two high-speed streams with flows that exceed 550 km/s. The solar wind proton speeds at STEREO/B are used to predict the solar wind speeds at STEREO/A under the assumptions of perfect corotation and radial solar wind flow with constant speed between the heliocentric radii of the two observatories. These assumptions are most likely to be valid during periods of minimal solar activity, as was the case in July 2008. The simplest frame in which to carry out the radial and longitudinal propagation is the idealized Carrington frame. In this representation each solar wind stream is a static Parker-spiral-like curve, and the observatories move in clockwise orbits (when viewed from the North) intersecting the streams. Both the radial and longitudinal separations are taken into account, but latitude separation is neglected. The two observatories encounter the same stream at different Carrington longitudes due to the difference in heliocentric distance, as illustrated in Fig. 3. The Carrington longitude at which STEREO/A is expected to encounter a given stream ($\varphi_{\mathrm{CARR\_Expected}}$) can be calculated (Eq. 1):

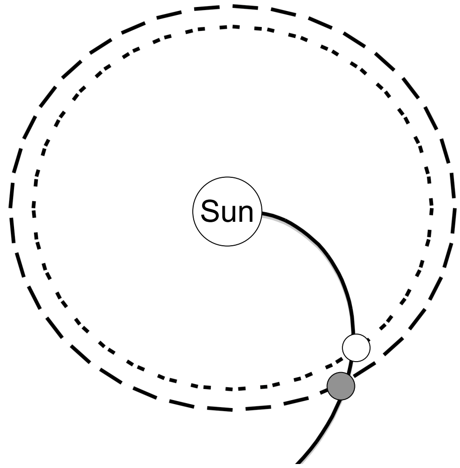

Fig. 3. Illustration of a solar wind stream in the idealized Carrington frame. The points at which the STEREO observatories intersect the stream are indicated with the small circles, open for AHEAD and filled for BEHIND.

$$\varphi_{\mathrm{CARR\_Expected}} = \varphi_{\mathrm{CARR\_B}} - \frac{\Omega_{\mathrm{Sun}}\,(R_B - R_A)}{V_{SW\_B}}, \quad (1)$$

where $\varphi_{\mathrm{CARR\_B}}$ is the Carrington longitude of STEREO/B, R_B and R_A are the respective observatory's orbital radius, and V_{SW_B} is the solar wind speed measured at STEREO/B. Ω_{Sun} is the angular speed at which the Sun rotates. For this study the solar equatorial photospheric speed of 14.38 degrees per day (Newton and Nunn, 1951) was assumed. Expected Carrington longitude is calculated rather than a time shift because the speed at which the observatories travel is not constant. Carrington longitudes can be converted to times using the STEREO orbit ephemerides.

Figure 4 shows both the expected and actual solar wind speeds measured by PLASTIC/AHEAD during July 2008 with the x-axis in terms of Carrington number. Error bars on the predicted speeds are ±100 km/s. The trends in the measured solar wind speed agree well with the prediction. Both high-speed streams were observed at their predicted Carrington longitudes. The stream interfaces, as defined by Burlaga (1974), were offset from their predicted times of arrival by several hours. The measured bulk speeds fell inside the ±100 km/s error bar of the predicted speed 95% of the time. The predicted and actual speeds agreed within 50 km/s 60% of the time.

Figure 5 shows the proton densities measured by PLASTIC/BEHIND during July 2008. The proton densities

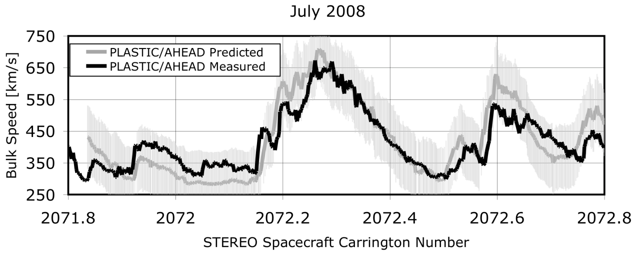

Fig. 4. Predicted and observed solar wind speed at PLASTIC/AHEAD during July 2008. An uncertainty of ±100 km/s on the predicted speed is shown with grey shading, while the observed values are given by the solid black curve.

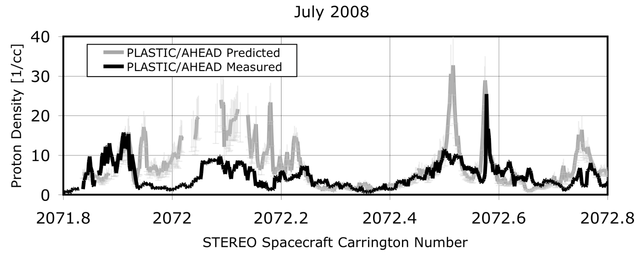

Fig. 6. Predicted and observed proton density at PLASTIC/AHEAD for July 2008. The uncertainty on the predicted density is shown with grey shading. The solid black curve shows the measured values.

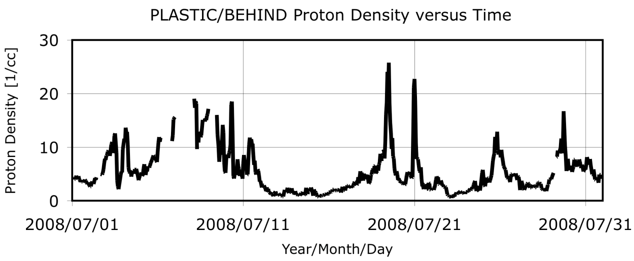

Fig. 5. Solar wind proton density measured by PLASTIC/BEHIND in July 2008.

measured by PLASTIC/BEHIND were used to predict the densities at PLASTIC/AHEAD by assuming constant flux through a spherical shell of radius R, and assuming the solar wind speed is the same at both observatories. In other words, the density measured at PLASTIC/BEHIND is scaled by a factor $(R_B/R_A)^2$, where R_B and R_A are the heliocentric distances of the two STEREO observatories.

Figure 6 shows the predicted and measured proton densities at PLASTIC/AHEAD. The uncertainty was calculated assuming the solar wind speed could change by up to 100 km/s between observations, and that the density measured at STEREO/BEHIND has an uncertainty of 10 percent or less. The trends in the proton densities agree with the predictions, but in some cases the magnitudes are off by more than a factor of two from the predicted values. The proton densities are lower than expected at STEREO/A prior to arrival of the first high-speed stream. This may be explained by the difference in slow solar wind speed between STEREO/B and STEREO/A, which was contrary to our assumption of constant solar wind speed. The density measured at STEREO/A immediately prior to the second high-speed stream agrees well with the predicted values. The density enhancement near CR 2072.5 is smaller than expected.

3 Discussion

Miyake et al. (2005a, b) conducted a correlation study using data from the "Nozomi" spacecraft and the Advanced Composition Explorer (ACE) when they were separated by greater than 50 degrees heliographic longitude. Solar wind speed measurements at "Nozomi" were obtained for H^+ or He^{++} when the solar wind speed was greater than 400 km/s. These were correlated with the solar wind speed measured by ACE by calculating a time lag needed to account for both solar rotation and the different heliocentric distances of the two spacecraft. The Miyake et al. (2005a, b) study took place during solar max conditions, so transient streams had to be removed from their data set. They found a correlation coefficient of 0.68 for longitude separations between 50° and 110°, and found that 90% of the solar wind speeds at Nozomi fell within 100 km/s of the value at ACE. Our study takes place under solar min conditions when there were no interplanetary coronal mass ejections (ICMEs), and includes proton density in addition to the solar wind proton speed.

Figure 7 shows the bulk speed measured at PLASTIC/AHEAD versus the speed measured at PLASTIC/BEHIND with appropriate time shifting. A linear fit forced to zero at the intercept has coefficient of determination R^2=0.69. 95% of the time solar wind speeds at PLASTIC/AHEAD fell within 100 km/s of the speed at PLASTIC/BEHIND. 60% of the time the speeds fell within 50 km/s of each other. The peak solar wind speed measured at STEREO/AHEAD is within 5% of the peak speed at STEREO/BEHIND for the first high-speed stream. In the case of the second high-speed stream the maximum speed recorded at STEREO/AHEAD is less than the maximum speed at STEREO/BEHIND by about 15%.

Figure 8 shows the measured proton density at PLASTIC/AHEAD versus the expected density based on measurements at PLASTIC/BEHIND. While a linear trend line can be fit through the data, the overall correlation is poor. This may be due in part to the assumption of constant solar wind speed. Incorporation of remote imaging data could potentially lead to better density predictions because the speed of

Table 1. Expected and observed times of stream interface arrival.

Arrival at STEREO/BEHIND	Expected time at STEREO/AHEAD	Arrival at STEREO/AHEAD	Difference [h]
9 July 2008, 23:00 UTC	13 July 2008, 23:00 UTC	13 July 2008, 16:00 UTC	−7
20 July 2008, 22:00 UTC	25 July 2008, 02:00 UTC	25 July 2008, 11:00 UTC	+9

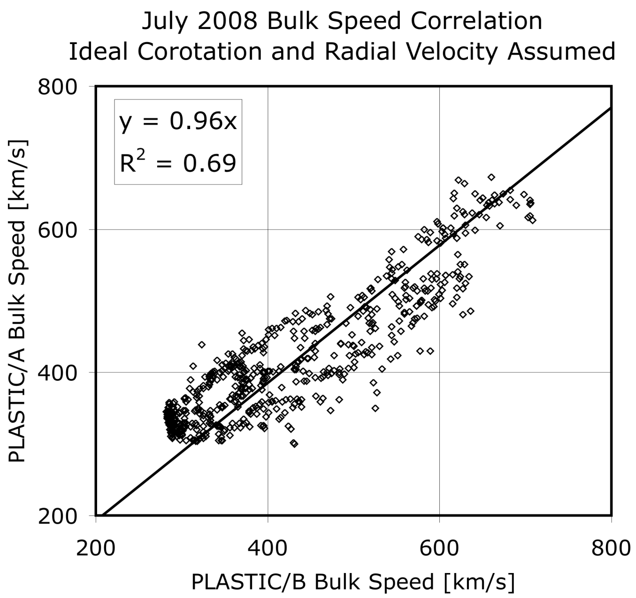

Fig. 7. Solar wind bulk speed correlation between PLASTIC/AHEAD and PLASTIC/BEHIND for July 2008.

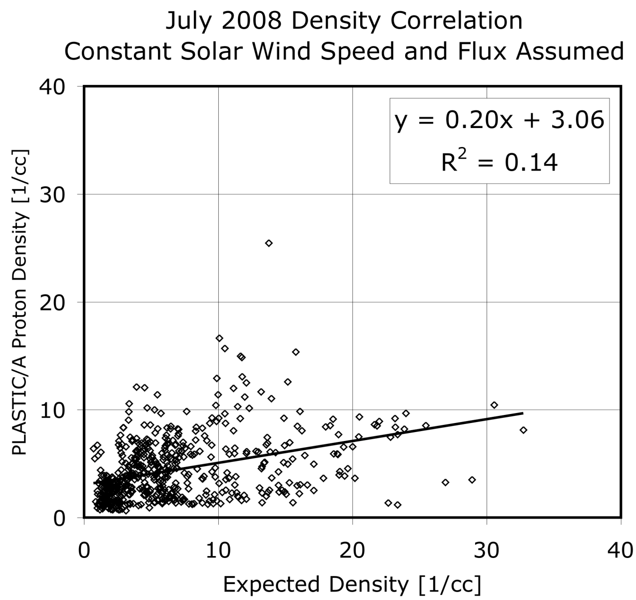

Fig. 8. Solar wind proton density correlation between PLASTIC/AHEAD and PLASTIC/BEHIND for July 2008.

the fast solar wind is related to the area of the coronal hole from which it emanates (cf. Nolte et al., 1976; Wang and Sheeley, 1990). Viewing changes in the boundaries of the coronal hole during the days between observations can indicate if the coronal hole is growing or shrinking, which would suggest the solar wind speed is increasing or decreasing. Assuming flux conservation the density estimate could then be revised. Another possible cause for poor density correlation is the evolution of SIR and CIR compression regions – they become steeper with radial distance, leading to greater compression. This is opposite to the trend of the ambient solar wind.

Table 1 lists the times-of-arrival of the interfaces between slow and fast solar wind streams at both STEREO observatories, the expected times-of-arrival at STEREO/AHEAD, and the difference between the expected and actual times. The differences between expected and actual arrival times are less than 10% of the total corotation times. The first stream (near CR 2072.3) arrived seven hours earlier than expected, and the second stream (near CR 2072.6) arrived nine hours later than expected. There are a number of possible explanations for the differences between expected and actual arrival times. These include: coronal hole drift with respect to the equatorial photosphere, evolution of the source region(s), and connecting to different parts of the same coronal hole, likely because of latitude separation.

Elliot et al. (2003) took data from ACE and propagated it out to *Ulysses* with the Zeus hydrodynamic code. The heliographic latitude separation between the spacecraft varied from 0 to 42 degrees during the time period included in their data set. They often found stream structures that were observed by both spacecraft when latitude separation was less than 15 degrees. However, the detailed structure in the speed and density changed between L1 and *Ulysses*, which Elliot et al. attribute to stream interactions.

4 Conclusions and future work

The overall solar wind speed profiles were similar between STEREO/BEHIND and STEREO/AHEAD during this period of minimal solar activity, in spite of heliographic latitude separations that exceeded 5° and longitude separations of about 60°. Therefore, a solar wind monitor at the L5

Lagrange point would augment our space weather forecasting capabilities for the Earth.

The simple technique presented here was used to predict the arrival time of two high-speed solar wind streams to within 10% of the total corotation time between two observation points separated by about 60° in longitude and more than 5° in heliographic latitude. Incorporating remote images of coronal holes should allow us to refine our predictions for both the arrival times and the measured in situ properties. However, with the rise of Solar Cycle 24 we expect the correlation between observations will decrease unless transient flows, such as ICMEs, are omitted.

Incorporating magnetic field data will be important for predicting geoeffectiveness. Long duration auroral activity typical of solar activity minimum periods has been linked to Alfvén waves with recurring southward Bz in high-speed streams. Future work would include Alfvénic fluctuations, to see if they can be predicted over the 60 degree longitude separation.

Acknowledgements. This work was supported under NASA contract NAS5-00132.

Topical Editor R. Forsyth thanks two anonymous referees for their help in evaluating this paper.

References

Akioka, M., Nagatsuma, T., Miyake, W., Ohtaka, K., and Marubashi, K.: The L5 mission for space weather forecasting, Adv. Space Res., 35, 65–69, doi:10.1016/j.asr.2004.09.014, 2005.

Baker, D. N., McPherron, R. L., Cayton, T. E., and Klebesadel, R. W.: Linear Prediction Filter Analysis of Relativistic Electron Properties at 6.6 RE, J. Geophys. Res., 95, 15133–15140, 1990.

Burlaga, L. F.: Interplanetary stream interfaces, J. Geophys. Res., 79, 3717–3725, 1974.

Elliott, H. A., McComas, D. J., and Riley, P.: Latitudinal extent of large-scale structures in the solar wind, Ann. Geophys., 21, 1331–1339, 2003, http://www.ann-geophys.net/21/1331/2003/.

Galvin, A. B., Kistler, L. M., Popecki, M. A., Farrugia, C. J., Simunac, K. D. C., Ellis, L., Möbius, E., Lee, M. A., Boehm, M., Carroll, J., Crawshaw, A., Conti, M., Demaine, P., Ellis, S., Gaidos, J. A., Googins, J., Granoff, M., Gustafson, A., Heirtzler, D., King, B., Knauss, U., Levasseur, J., Longworth, S., Singer, K., Turco, S., Vachon, P., Vosbury, M., Widholm, M., Blush, L. M., Karrer, R., Bochsler, P., Daoudi, H., Etter, A., Fischer, J., Jost, J., Opitz, A., Sigrist, M., Wurz, P., Klecker, B., Ertl, M., Seidenschwang, E., Wimmer-Schweingruber, R.F., Koeten, M., Thompson, B., and Steinfeld, D.: The plasma and suprathermal ion composition (PLASTIC) investigation on the STEREO observatories, Space Sci. Rev., 136, 437–486, doi:10.1007/s11214-007-9296-x, 2008.

Leske, R. A., Mewaldt, R. A., Mason, G. M., Cohen, C. M. S., Cummings, A. C., Davis, A. J. Labrador, A. W., Miyasaka, H., Stone, E. C., Wiedenbeck, M. E., and von Rosenvinge, T. T.: STEREO and ACE Observations of CIR Particles, in: Proceedings of the 7th Annual Astrophysics Conference/Particle Acceleration and Transport in the Heliosphere and Beyond, Kauai, Hawaii, 7–13 March 2008.

Li, X., Temerin, M., Baker, D. N., Reeves, G. D., and Larson, D.: Quantitative Prediction of Radiation Belt Electrons at Geostationary Orbit Based on Solar Wind Measurements, Geophys. Res. Lett., 28, 1887–1890, 2001.

Mason, G. M., Desai, M. I., Mall, U., Korth, A., Bucik, R., von Rosenvinge, T. T., and Simunac, K. D.: In situ observations of CIRs on STEREO, Wind, and ACE During 2007–2008, Solar Phys., 256, 393–408, doi:10.1007/s11207-009-9367-0, 2009.

Miyake, W., Saito, Y., Hayakawa, H., and Matsuoka, A.: On the correlation of the solar wind observed at the L5 point and at the Earth, Adv. Space Res., 36, 2328–2332, doi:10.1016/j.asr.2004.06.019, 2005a.

Miyake, W., Saito, Y., Hayakawa, H., and Matsuoka, A.: A study of correlation between solar wind data observed at two points in interplanetary space during the recent solar maximum, Solar Phys., 227, 355–370, doi:10.1007/s11207-005-2100-8, 2005b.

Newton, H. W. and Nunn, M. L.: The Sun's rotation derived from sunspots 1934–1944 and additional results, Mon. Not. R. Astron. Soc., 111, 413–421, 1951.

Nolte, J. T., Krieger, A. S., Timothy, A. F., Gold, R. E., Roelof, E. C., Vaiana, G., Lazarus, A. J., Sullivan, J. D., and McIntosh, P. S.: Coronal Holes as Sources of Solar Wind, Solar Phys., 46, 303–322, 1976.

Schwenn, R.: Large-scale structure of the interplanetary medium, in: Physics of the Inner Heliosphere 1: Large-Scale Phenomena, edited by: Schwenn, R. and Marsch, E., Springer-Verlag, Berlin, 99–181, 1990.

Simunac, K. D. C., Kistler, L. M., Galvin, A. B., Lee, M. A., Popecki, M. A., Farrugia, C., Moebius, E., Blush, L. M., Bochsler, P., Wurz, P., Klecker, B., Wimmer-Schweingruber, R. F., Thompson, B., Luhmann, J. G., Russell, C. T., and Howard, R. A.: In situ observations of solar wind stream interface evolution, Solar Phys., online first, doi:10.1007/s11207-009-9393-y, 2009.

Tsurutani, B. T., Gonzalez, W. D., Gonzalez, A. L. C., Guarnieri, F. L., Gopalswamy, N., Grande, M., Kamide, Y., Kasahara, Y., Lu, G., Mann, I., McPherron, R., Soraas, F., and Vasyliunas, V.: Corotating solar wind streams and recurrent geomagnetic activity: A review, J. Geophys. Res., 111, A07S01, doi:10.1029/2005JA011273, 2006.

Wang, Y.-M. and Sheeley, N. R.: Solar wind speed and coronal flux-tube expansion, Astrophys. J., 355, 726–732, 1990.

Webb, D. F., Biesecker, D. A., Gopalswamy, N., St. Cyr, O. C., Davila, J. M., Thompson, B. T., and Simunac, K. D. C.: Using STEREO-B as an L5 space weather pathfinder mission, Space Weather, in review, 2009.

Zhang, Y., Sun, W., Feng, X. S., Deehr, C. S., Fry, C. D., and Dryer, M.: Statistical analysis of corotating interaction regions and their geoeffectiveness during solar cycle 23, J. Geophys. Res., 113, A08106, doi:10.1029/2008JA013095, 2008.