Helio2050 White Paper: Magnetic Reconnection Science in the Outer Heliosphere

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What We Know: There is plentiful evidence of Alfvénic reconnection exhausts across inner heliosphere current sheets of many spatial scales. Most events are observed in time scales ranging from the highest plasma instrument cadence available (>3 s) to several minutes with a few known examples also reported at the hour time scale of Heliospheric Current Sheet (HCS) crossings [e.g., *Gosling et al.*, 2005a; 2005b; 2006a; 2006b; 2006c; 2007]. These exhausts are the "smoking guns" of magnetic reconnection X-lines that change the magnetic topology and allow the ions and electrons to cross a current sheet (CS) boundary along the magnetic field. Magnetic reconnection is known to be a key mechanism that ultimately converts magnetic field energy into bulk flow energy, particle acceleration and plasma heating [e.g., *Drake et al.*, 2009; *Phan et al.*, 2014]. It may also enable the growth of large-scale magnetic field structures known as magnetic islands when several X-lines are present at the same CS. Inner heliosphere reconnection exhausts are mostly observed in a low ion beta ($\beta i<1$) regime in agreement with the background βi-distribution (Figure 1), where βi is the ratio of proton plasma pressure to magnetic field pressure.

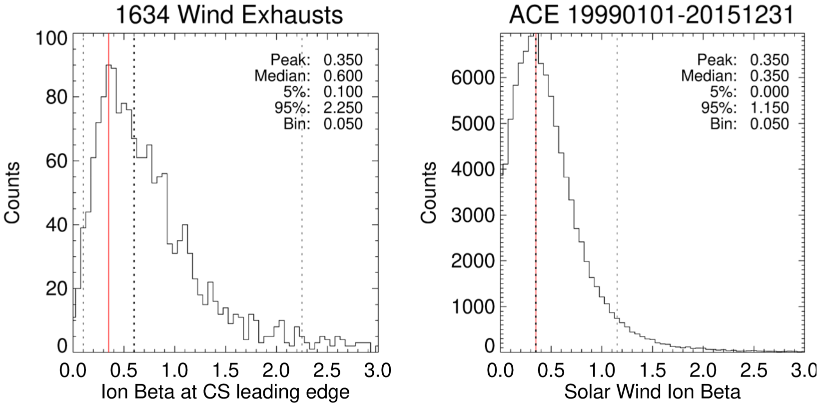

Figure 1: Histogram distribution of the ion plasma beta (βi) as observed by the Wind satellite (left) at the leading edge of 1634 confirmed reconnection exhausts for the time period July 2004 to Dec. 2014. The distribution of the 1-hour cadence βi as observed by the ACE satellite for 17 years of operations (99356 finite value data points) is shown on the right with a $\beta i=0.35$ median distribution as compared with a median $\beta i=0.60$ in the set of confirmed exhausts by the Wind satellite (left).

Theory predicts that magnetic reconnection will initiate spontaneously at an inner heliosphere CS when the normal width of the CS is on the order of 1-2 *di*. Here, 1 $di=c/\omega_{pi}$ is the ion inertial length scale, c is the speed of light and ω_{pi} is the ion plasma frequency. The ACE satellite, e.g., measured a median *di*=100 km at 1 AU in a 17-year period with 90% of the 1-hour cadence *di* measurements in a 55-170 km range. Reconnection takes place within highly localized diffusion regions, which are nearly impossible to detect in the vastness of the solar wind. However, the process reveals itself in the two oppositely directed exhausts that may travel very far along the CS from the X-line. The theoretical maximum jet speed is the local Alfvén speed $V_A=B/\surd(\rho\mu_0)$ in the CS moving frame of reference. In the absence of local CS structure, each exhaust expands freely in a normal direction as it propagates away from the X-line. The rate of this outflow expansion is given by the rate at which plasmas and magnetic fields are processed through the diffusion region between the inflow and the outflow.

In stark contrast to the inner heliosphere, we only have a very rudimentary knowledge of the outer heliosphere and, in particular, the boundary with the local interstellar medium (LISM). Prior to encountering the heliopause (HP) on 5 Nov 2018, the Voyager 2 spacecraft observed an unexpected "magnetic barrier" with an average 0.4 nT magnetic field (**B**) strength [*Burlaga et al.*, 2019], and the Voyager Plasma Science (PLS) experiment measured surprisingly "warmer-than-expected" 30,000-50,000 K ion temperatures [*Richardson et al.*, 2019] in the adjacent LISM. *Richardson et al.* [2019] proposed that the high temperatures could be due to more plasma compression than expected, or plasma heating associated with magnetic reconnection. Large- and small-scale simulations suggest that magnetic reconnection should occur in the inner heliosheath (HS), since the termination shock may result in HS field compression and closely spaced HCSs [e.g., *Lazarian & Opher*, 2009; *Drake et al.*, 2010; *Pogorelov et al.*, 2017]. *Richardson et al.* [2016] show how **B** observed by Voyager is more unipolar in the outer HS with fewer HCS crossings than expected, a possible indication that magnetic reconnection is active in the HS.

R	**Np**	**Tp**	**B**	**V_A**	**Pb**	**Pp**	**βi**	**di**
(AU)	**(cm^{-3})**	**(K)**	**(nT)**	**(km/s)**	**(pPa)**	**(pPa)**		**(km)**
20	0.020	10000.	0.15	23.1	0.00895	0.00276	0.31	1610.
80	0.001	4000.	0.03	20.7	0.00036	0.00006	0.15	7201.
100.	0.002	50000.	0.05	24.4	0.00099	0.00138	1.39	5092.
120.	0.040	70000.	0.40	43.6	0.06366	0.03866	0.61	1139.
130.	0.120	30000.	0.70	44.1	0.19496	0.04970	0.25	657.
150.	0.120	50000.	0.70	44.1	0.19496	0.08284	0.42	657.
500.	0.100	7500.	0.30	20.7	0.03581	0.01035	0.29	720.

Table 1 (above) provides average values of plasma density (Np), proton temperature (Tp) and magnetic field strength (B) with radial distance in the outer heliosphere that may be used to estimate approximate values for the important *di*-scale, Alfvén speed (V_A) and ion plasma βi=Pp/Pb, where Pb and Pp are the magnetic field and proton plasma pressures, respectively. Values sunward of 100 AU were estimated from *Köhnlein* [1996]. Values at 100-130 AU were obtained by Voyager [*Burlaga et al.*, 2019; *Gurnett and Kurth*, 2019; *Richardson et al.*, 2019] and values at 130-500 AU are estimates based on LISM values at the present Voyager 2 position, IBEX estimates [*McComas et al.*, 2015; *Zirnstein et al.*, 2016], and the assumption that the density and magnetic field strength eventually decrease with distance in a more tenuous LISM. The estimated βi<2 regime of the outer heliosphere suggests that magnetic reconnection could very well be active across local CSs at 20-500 AU, since the expected βi values are very similar to those confirmed across exhausts of the inner heliosphere [*Gosling et al.*, 2006b; Figure 1].

What is the Problem? *We do not know* if magnetic reconnection continues to rupture current sheets in the solar wind at all radial distances from the Sun beyond Jupiter, through the HS, across the HP, or even beyond in the LISM itself; mainly because the Voyager spacecraft instruments were not *designed* to measure the tenuous plasmas of the low-B outer heliosphere. ***Is reconnection truly a universal space plasma process that occurs in the whole heliosphere and beyond*?** Does it "crack open" the HP and enable the generation of important structures? Does it generate magnetic field structures, which are interchangeably known as either "magnetic islands" or "magnetic flux ropes" in the HS and across the HP itself, as theorized by several authors [*Drake et al.*, 2010; *Opher et al.*, 2011; *Swisdak et al.*, 2013]? If small-scale CSs form naturally by turbulence in the outer heliosphere and in the adjacent LISM, as in the inner heliosphere, then the important scale to resolve in the outer heliosphere and LISM is the proton gyro-radius ρ_i, which is related to the ion inertial scale as $d_i=\rho_i/\sqrt{\beta_i}$. This is because the correlation scale L of the turbulence is expected to be very large compared to ρ_i, so the CS is highly anisotropic by the time it reaches the gyro-radius. *However, the nature of turbulence in the outer heliosphere and in the LISM are unknown*. If magnetic reconnection is confirmed in the outer heliosphere from its telltale exhaust signatures, then it may also lead to electron acceleration and further plasma heating, e.g., through multi-island coalescence and Fermi acceleration processes [e.g., *Drake et al*., 2006; *Oka et al*., 2010]. Finding evidence of Alfvénic exhausts across small-scale CSs associated with turbulence or large-scale HCSs at these remote outer heliosphere distances, within the HS and specifically within the "magnetic barrier" and the HP boundary itself, would suggest that magnetic reconnection may be crucial in understanding the nature and the structure of our outer heliosphere boundaries, such as the HS and the HP.

The low-cadence Voyager measurements and the instrument uncertainty ranges of the magnetic field (magnitude, direction) and the plasma moments of the ion velocity distribution, even when data are available due to telemetry restrictions and science mode of operations, prevent a high-quality CS survey for unambiguous reconnection exhaust evidence to suggest whether magnetic reconnection is important in the outer heliosphere dynamics of magnetic field boundaries.

In 2050, we envision that Heliophysics will have matured to the point where we can claim that we understand the *outer heliosphere* and its boundaries at least as well as we understand our inner heliosphere. Ever since the 1960's, the physics of magnetic field reconnection has played an integral part in space plasma physics, and in our understanding of magnetic structure formation in space. It will certainly play a crucial role in our understanding of the outer heliosphere in the year 2050.

References:

Burlaga, L. F., *et al*. (2019), Magnetic field and particle measurements made by Voyager 2 at and near the heliopause, *Nat. Astr.*, doi:10.1038/s41550-019-0920-y.

Drake, J. F., *et al*. (2006), Electron acceleration from contracting magnetic islands during reconnection, *Nature*, doi:10.1038/nature05116.

Drake, J. F., *et al*. (2009), Ion heating resulting from pickup in magnetic reconnection exhausts, *J. Geophys. Res*., doi:10.1029/2008JA013701.

Drake, J. F., *et al*. (2010), A magnetic reconnection mechanism for the generation of anomalous cosmic rays, *Astrophys. J.*, doi:10.1088/0004-637X/709/2/963.

Gosling, J. T., *et al*. (2005a), Direct evidence for magnetic reconnection in the solar wind near 1 AU, *J. Geophys. Res*., doi:10.1029/2004JA010809.

Gosling, J. T., *et al*. (2005b), Magnetic disconnection from the Sun: Observations of a reconnection exhaust in the solar wind at the heliospheric current sheet, *Geophys. Res. Lett.,* doi:10.1029/2005GL022406.

Gosling, J. T., *et al*. (2006a), Petschek-type reconnection exhausts in the solar wind well beyond 1 AU: ULYSSES, *Astrophys. J.*, doi:10.1086/503544.

Gosling, J. T., *et al*. (2006b), Petschek-type magnetic reconnection exhausts in the solar wind well inside 1 AU: Helios, *J. Geophys. Res*., doi:10.1029/2006JA011863.

Gosling, J. T., *et al.* (2006c), Magnetic reconnection at the heliospheric current sheet and the formation of closed magnetic field lines in the solar wind, *Geophys. Res. Lett*., doi:10.1029/2006GL027188.

Gosling, J. T., *et al*. (2007), Direct evidence for prolonged magnetic reconnection at a continuous X-line within the heliospheric current sheet, *Geophys. Res. Lett.*, doi:10.1029/2006GL029033.

Gurnett, D. A., and W. S. Kurth (2019), Plasma densities near and beyond the heliopause from the Voyager 1 and 2 plasma wave instruments, *Nat. Astr.*, doi:10.1038/s41550-019-0918-5.

Köhnlein, W. (1996), Radial dependence of solar wind parameters in the ecliptic (1.1 Rs-61 AU), *Solar Physics*, doi:10.1007/BF00153841.

Lazarian, A., and M. Opher (2009), A model of acceleration of anomalous cosmic rays by reconnection in the heliosheath, *Astrophys. J.*, doi:10.1088/0004-637X/703/1/8.

McComas, D. J., *et al*. (2015), Warmer local interstellar medium: A possible resolution of the Ulysses-IBEX enigma, *Astrophys. J.*, doi:10.1088/0004-637X/801/1/28.

Oka, M., *et al*. (2010), Electron acceleration by multi-island coalescence, *Astrophys. J.*, doi:10.1088/0004-637X/714/1/915.

Opher, M., *et al*. (2011), Is the magnetic field in the heliosheath laminar or a turbulent sea of bubbles? *Astrophys. J.*, doi:10.1088/0004-637X/734/1/71.

Phan, T. D., *et al*. (2014), Ion bulk heating in magnetic reconnection exhausts at Earth's magnetopause: Dependence on the inflow Alfvén speed and magnetic shear angle, *Geophys. Res. Lett*., doi:10.1002/2014GL061547.

Pogorelov, N. V., *et al*. (2017), Three-dimensional features of the outer heliosphere due to coupling between the interstellar and heliospheric magnetic field. V. The bow wave, heliospheric boundary layer, instabilities, and magnetic reconnection, *Astrophys. J.,* doi:10.3847/1538-4357/aa7d4f.

Richardson, J. D., *et al.* (2016), Voyager observations of magnetic sectors and heliospheric current sheet crossings in the outer heliosphere, *Astrophys. J.*, doi:10.3847/0004-637X/831/2/115.

Richardson, J. D., *et al*. (2019), Voyager 2 plasma observations of the heliopause and interstellar medium, *Nat. Astr.*, doi:10.1038/s41550-019-0929-2.

Swisdak, M., J. F. Drake, and M. Opher (2013), A porous, layered heliopause, *Astrophys. J. Lett.*, doi:10.1088/2041-8205/774/1/L8.

Zirnstein, E. J., *et al*. (2016), Local interstellar magnetic field determined from the Interstellar Boundary Explorer ribbon, *Astrophys. J. Lett*., doi:10.3847/2041-8205/818/1/L18.