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Magnetic helicity observations in the inner heliosphere

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Magnetic helicity is one of the invariants in ideal magnetohydrodynamics such as the total energy and cross helicity, which represents the torsion of magnetic lines of force within a volume. It plays an important role in the dynamics of turbulent magnetized plasmas, affecting the direction and nature of turbulent cascades, magnetic recombination, particle acceleration, and the large-scale evolution of magnetic structures extending from the Sun to the heliosphere. Understanding their behavior, especially their spatial distribution and spectral properties, is key to unraveling the complex processes that govern solar wind turbulence and its solar origin.

Earlier spacecraft observations of magnetic helicity in solar wind turbulence in the 1980s revealed that the magnetic helicity changes the sign (sense of field rotation sense around the flow direction) whimsically [1], and that the helicity spectrum scales in the fashion of the Richardson-Kolmogorov inertial range with a dimensional correction by the wavenumber or the spacecraft-frame frequency (when applying Taylor's frozen-in flow hypothesis). This apparent randomness led to the mainstream view that there is no favorable chiral nature to solar wind turbulence at inertial scales, and the topic of sign-determining helicity was considered largely settled, except for its presence at larger energy-bearing scales that may be associated with solar origin, and further investigation was considered largely unnecessary.

However, beginning around 2010, studies reexamining magnetic helicity with refined observational techniques, different plasma environments (e.g., the magnetospheric outer layers of planets), and improved temporal resolution began to question the universality of the random sign paradigm [2]. These studies suggested that systematic helicity signatures may exist under certain conditions and with different analysis methods. Unprecedented high temporal resolution magnetic field measurements from the Parker Solar Probe and Solar Orbiter deep in the inner heliosphere and from BepiColombo towards Mercury provide a unique opportunity to revisit the fundamental nature of solar wind turbulence close to its origin. This study is motivated by the following central question: Does magnetic helicity in the solar wind near the Sun exhibit random sign variability observed within 1 AU, or does a systematic sign feature emerge in the new high-resolution data set acquired in the nascent solar wind?

In view of three on-going spacecraft performing magnetic field measurements in situ, we first develop an estimator of the magnetic helicity spectrum for the magnetic field data using the observational fact that the wavevector of the turbulent solar wind is nearly perpendicular to the large-scale magnetic field, and apply the spectral estimator to the three spacecraft data. This anisotropy allows certain relationships to be established between the components of the magnetic field spectral tensor, to be established and allows helicity to be estimated without the need for multipoint measurements or full knowledge of the 3-D magnetic field information. However, assumptions such as Taylor's frozen flow hypothesis are commonly used. By applying this spectral estimator to high-frequency data from three spacecraft, the sign and magnitude of the magnetic helicity can be systematically analyzed over the inertial and the momentum range as a function of radial distance, solar wind flow type, and solar activity.

Systematic trends, especially with respect to signs, if confirmed by ongoing analyses, could have a profound impact on the understanding of solar wind turbulence. The presence of systematic helicity suggests a break in the mirror symmetry of turbulent fluctuations, which could radically alter cascade dynamics, potentially facilitating or suppressing energy transfer across scales. Non-zero helicity is intrinsically associated with circularly polarized light waves, suggesting that modes such as Alfvén ion cyclotron waves and kinetic Alfvén waves [3, 4] may transport helicity and contribute to plasma heating and dissipation. Furthermore, net magnetic helicity transported from the Sun may play a role in the large-scale structure and evolution of the heliospheric magnetic field.

Reference

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