Research Progress on Alfvén Waves in the Solar Wind: Postprint

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Abstract

Alfvén waves are ubiquitous in the solar wind and are of significant importance for the heating and acceleration of plasma therein. Recent research progress on Alfvén waves in the solar wind is summarized from the aspects of solar wind structures, solar wind turbulence, solar wind global models, plasma instabilities (parametric decay instability and firehose instability), and solar wind heating and acceleration. In combination with current research trends, prospects for future Alfvén wave research are discussed from three directions: sub-Alfvénic solar wind, solar wind global models, and the solar source region.

Full Text

Preamble

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Advances in Alfvén Wave Research in the Solar Wind

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Abstract

Alfvén waves are ubiquitous in the solar wind and play a crucial role in plasma heating and acceleration. This paper reviews recent advances in Alfvén wave research in the solar wind, covering solar wind structures, solar wind turbulence, global solar wind models, plasma instabilities (parametric decay instability and firehose instability), and solar wind heating and acceleration. Based on current research trends, future investigations of Alfvén waves are anticipated in three directions: sub-Alfvénic solar wind, global solar wind models, and solar source regions.

Keywords: waves, plasmas, solar wind, magnetohydrodynamics (MHD), magnetic fields

The solar wind is a supersonic, magnetized plasma that continuously streams outward from the solar corona, composed primarily of electrons, protons, alpha particles, and other heavy ions. It fills the entire heliosphere and can propagate to distances beyond 100 astronomical units (au) in interplanetary space, where it exhibits rich collisionless plasma phenomena (such as magnetohydrodynamic waves, turbulence, and magnetic structures across various scales) and involves numerous plasma physical processes (including wave excitation, propagation and energy dissipation, plasma instabilities, and solar wind acceleration and heating through magnetic reconnection). The solar wind is generally classified into three categories: fast solar wind (with speeds of 500–800 km/s), slow solar wind (300-500 km/s), and transient/episodic events (such as interplanetary coronal mass ejections, magnetic flux ropes, and magnetic clouds, with speeds ranging from several hundred to 2000 km/s).

The properties and evolution of solar wind structures exhibit multi-scale variations in both time and space, primarily related to their source regions on the Sun and local physical processes. Large-scale solar wind structures (such as magnetic clouds or interplanetary coronal mass ejections) are not only scientifically significant but can also trigger hazardous space weather, causing unpredictable impacts on ground- and space-based technological infrastructure, satellite navigation and communication systems, and power transmission equipment. Small-scale solar wind structures (such as magnetic field switchbacks, magnetic discontinuities, and small-scale magnetic flux ropes) may be more closely related to particle kinetic processes, involving particle velocity distributions in the plasma and energy transfer and dissipation produced by Alfvén wave instability processes, making the solar wind a natural plasma physics laboratory.

Alfvén waves are one of the fundamental wave modes in magnetohydrodynamics and are ubiquitous in the solar wind. Basic knowledge about Alfvén waves can be found in relevant textbooks. The occurrence rate of Alfvén wave events in the trailing edges of high-speed solar wind is approximately twice that in slow-speed solar wind, with relatively high Alfvénicity (i.e., the correlation between perturbed velocity and magnetic field components, used to characterize how closely the perturbation properties approach those of Alfvén waves). In contrast, slow solar wind typically exhibits lower Alfvénicity, greater variations in plasma parameters, and more mixed non-Alfvénic structures. (Note: "Alfvén waves" primarily describes solar wind perturbations that closely match theoretical expectations, i.e., those with high Alfvénicity. Perturbations with lower Alfvénicity but still possessing some Alfvén wave characteristics are generally referred to as "Alfvénic fluctuations," indicating that they may contain other wave modes or structures in addition to Alfvén waves. Sometimes, for descriptive uniformity, the literature does not make a clear distinction between the two, requiring case-by-case judgment.)

Solar wind turbulence plays an important role in solar wind formation, energetic particle acceleration, plasma heating, and cosmic ray propagation. When Alfvén waves dominate, it is also called Alfvén turbulence. The nonlinear interaction between counter-propagating Alfvén waves can drive solar wind turbulence and cause energy cascade. The properties and evolution of turbulence are not only closely related to Alfvén waves and the local plasma background environment but are also influenced by various plasma physical processes (such as plasma instabilities, wave reflection, excitation of counter-propagating waves, and wave-related resonant and non-resonant interaction processes), which transfer and dissipate wave energy and may alter turbulence properties.

Numerous plasma physical processes in solar wind turbulence and the wide range of background plasma parameters can satisfy specific plasma parameter threshold conditions, triggering corresponding plasma instabilities (such as parametric decay instability and firehose instability) that excite specific plasma waves. Through wave-particle interactions or turbulence cascade, these processes heat the plasma and cause changes in particle kinetic behavior and solar wind plasma properties. For more comprehensive and detailed introductions to the theoretical and observational studies of solar wind turbulence, readers may refer to review articles.

This paper focuses on Alfvén wave research in the solar wind, combining the latest satellite observational results to systematically review and summarize research progress on solar wind structures (such as magnetic field switchbacks, magnetic discontinuities, magnetic flux ropes/tubes, and slow solar wind), solar wind turbulence (including physical processes and counter-propagating waves), global solar wind models, plasma instabilities in the solar wind (parametric decay instability and firehose instability), and solar wind heating and acceleration. Based on this summary, future research directions and development trends are discussed.

2. Structures in the Solar Wind

Solar wind structures exhibit different properties and evolution across various temporal and spatial scales, which are closely linked to both their source regions on the solar surface and local physical processes. Large-scale structures (such as interplanetary coronal mass ejections) may carry information about source region structures and physical processes and can trigger hazardous space weather that affects the normal operation of ground- and space-based equipment. Smaller-scale structures (such as magnetic field switchbacks and magnetic discontinuities) are likely generated locally, enabling studies of the underlying physical mechanisms and making the solar wind a natural plasma physics laboratory. Here we mainly introduce several structures related to Alfvén waves in the solar wind, including magnetic field switchbacks, magnetic discontinuities, magnetic flux ropes/tubes, interplanetary coronal mass ejections, and slow solar wind. Below we discuss the relationship between Alfvén waves and these structures, related physical processes, and their roles.

2.1 Magnetic Field Switchbacks

Magnetic field observations from Parker Solar Probe (PSP) during its first approach to the Sun are shown in [Figure 1: see original paper], with the upper and lower panels corresponding to observation durations of 10 days and 2 hours, respectively. The figure reveals rapid polarity reversals in the radial magnetic field B_R, a phenomenon known as magnetic field switchbacks (as illustrated in [Figure 1: see original paper]), with magnetic field deflection angles ranging from a few degrees to nearly 180°. This phenomenon was ubiquitous during the observation period and became one of PSP' s most striking results. These switchback structures are self-similar and affect the dynamic variation of the magnetic field. Wavelet analysis of satellite data shows that the two-dimensional joint distribution of normalized residual energy and cross helicity exhibits characteristics indicating that these perturbations are relatively pure Alfvén waves, similar to previous Helios observations. Magnetic field switchbacks cause the cross helicity at shorter wavelet scales to become negative. These switchbacks often occur in regions of locally enhanced radial velocity (or jets) and exhibit velocity-magnetic field correlations in all components, characteristic of large-amplitude Alfvén waves propagating outward from the Sun.

Multiple PSP perihelion observations demonstrate that large-amplitude Alfvénic perturbations in the form of magnetic field switchbacks are ubiquitous in the inner heliosphere, associated with increased alpha particle abundance, Mach number, plasma β (the ratio of thermal to magnetic pressure), and pressure, along with decreased magnetic field strength and electron temperature. Statistical analysis of PSP' s perihelion observations, particularly particle and plasma wave characteristics, reveals that 73% of switchback events exhibit Alfvén wave-like properties with essentially constant magnetic field strength, while the remaining 27% show compressibility with variations in both magnetic field strength and density perturbations. The longitudinal spacing of these plasma structures is comparable to the size of supergranular cells, suggesting that these switchbacks originate near the leading edges of diverging magnetic funnels associated with network magnetic fields and are generated through interchange reconnection processes.

Analysis of magnetic and plasma perturbations related to magnetic field switchbacks reveals three distinct structural characteristics: (1) Alfvénic structures where magnetic field components vary while magnetic field strength remains constant; (2) compressive structures where both magnetic field components and strength vary; and (3) magnetic field reversal structures, which can be considered extreme examples of Alfvénic switchbacks. These structural boundaries and plasma velocity perturbations indicate that magnetic field switchbacks are localized magnetic flux tubes with higher parallel velocity and β values compared to the surrounding background plasma (likely due to hotter plasma inside the flux tubes). Reconstruction using a new Grad-Shafranov algorithm reveals that magnetic field switchbacks can appear when spacecraft cross such flux tube/rope structures. These magnetic field switchback structures may also represent local deformations of magnetic flux tubes, corresponding to the saturated stage of firehose instability development.

Analytical models of plasma dynamics predict that magnetic field switchbacks are more likely to occur in regions where solar wind plasma expansion is stronger, with their fraction increasing with heliocentric distance and their gradients tending to be perpendicular to the mean magnetic field direction. When the relative amplitude of Alfvén waves increases due to solar wind expansion, the resulting compression steepens the wave profile while maintaining an almost constant magnetic field strength. Model results are consistent with related phenomena in previous observational and numerical simulation studies, indicating that magnetic field switchbacks can form through the nonlinear evolution of small-amplitude Alfvén waves originating from the coronal base. Some magnetic field switchbacks observed by PSP may also be natural consequences of amplitude growth in spherically polarized Alfvén waves propagating outward from the Sun, i.e., rotational discontinuities formed by large-amplitude (nonlinear) Alfvén waves. Numerical simulations of Alfvén wave turbulence can reproduce many observed features of switchbacks, including the velocity-magnetic field correlation of Alfvén waves, spherical polarization (low magnetic compressibility), and increasing volumetric filling factor with radial distance.

Magnetohydrodynamic numerical simulations of large-amplitude Alfvénic perturbation evolution, accounting for magnetic field switchbacks and constant magnetic pressure, show that as long as the background solar wind does not have strong density perturbations or large gradients in other parameters (such as the absence of solar wind streams or magnetic field shear), magnetic field switchbacks can survive for hundreds of Alfvén crossing times before being destroyed by parametric decay instability, allowing them to persist to the heliocentric distances where spacecraft observe them. Otherwise, they become unstable or are completely destroyed on shorter timescales. These results support the hypothesis that magnetic field switchback (or jet) structures originate in the low corona.

Magnetic field switchbacks in the solar wind are often accompanied by Alfvénic velocity spikes, with temperature increase being a notable characteristic of such spikes. To understand these phenomena, discontinuities have been introduced into interchange reconnection models between open funnels and closed loops with different magnetic helicities. This approach not only accelerates jets from newly opened closed loops but also excites Alfvénic spikes along the reconnected open flux tubes, reproducing observational features such as the temporal impulsiveness and spatial asymmetry of Alfvénic perturbations, compressibility of Alfvénic spikes, temperature enhancement within pulse structures, and density variations. Thus, studying the formation mechanism of magnetic switchback structures requires consideration of the radial nonlinear evolution of Alfvénic spikes.

The exact origin of magnetic field switchbacks remains undetermined. Some researchers argue that switchbacks are locally formed magnetic twist structures rather than originating from regions of opposite polarity on the solar surface. Existing theoretical models focus on explaining partial magnetic and plasma dynamic features of switchbacks and cannot fully account for many observational characteristics. Increasing perihelion detection data from satellites provide more observational constraints on the generation mechanism of magnetic field switchbacks, requiring corresponding theoretical models to explain not only pure Alfvénic perturbations but also those magnetic and plasma features. Theoretically, both firehose instability and wave parametric decay instability can explain some observed features in the formation process of magnetic field switchbacks and serve as candidate mechanisms, but more comprehensive theoretical models incorporating actual observations are needed.

Some studies suggest that switchbacks do not cause magnetic shear in the background field, and their boundaries can be regarded as rotational or tangential discontinuities, with rotational discontinuities appearing more frequently.

In interchange reconnection models between open funnels and closed loops with different magnetic helicities, introducing discontinuities along the guide field direction not only accelerates jets from newly opened closed loops but also excites Alfvénic pulses/spikes that propagate along the reconnected open flux tubes. Model results reproduce the main observational features of Alfvénic pulses/spikes observed by PSP, helping to further improve understanding of the physical mechanisms underlying magnetic switchback structure formation.

2.2 Magnetic Field Discontinuities

The presence of magnetic discontinuity structures affects the determination of the de Hoffmann-Teller frame for solar wind plasma flow, consequently influencing estimates of the Alfvénicity of solar wind plasma perturbations. Generally, Alfvénic perturbations from solar winds of different scales should have different de Hoffmann-Teller frames. Based on this principle, some new approaches obtain a time-varying de Hoffmann-Teller frame (rather than the constant frame commonly used in previous studies), which can effectively reduce the influence of magnetic discontinuity structures, yield better Walén test results, and correspond to smaller convection electric fields.

The existence of magnetic field directional discontinuities can cause non-uniformity in the magnetic vector direction variation of arc-polarized Alfvén waves. Numerical simulations of surface Alfvén waves perpendicular to magnetic discontinuities show that the nonlinear self-deformation of these unidirectionally propagating waves causes cascading of magnetic transverse wave energy, which may strongly influence the turbulent dissipation rate of outward-propagating Alfvén waves in the solar wind.

Phase steepening of large-amplitude Alfvén waves propagating parallel to discontinuities can produce proton energization. Hybrid simulations reveal that dispersion effects cause wave breaking through phase steeping, after which the resulting compressive perturbations can efficiently transfer wave energy to protons. At the edges of wave steepening, proton scattering causes non-adiabatic perpendicular heating of protons, while the parallel electric field at the wave front regulates proton acceleration along the field. The entire system reaches a steady state when field-aligned beams appear at the Alfvén speed, while compressive wave modes are mostly damped. These processes are important for the dynamic evolution of Alfvénic solar wind.

2.3 Magnetic Flux Ropes/Tubes

In recent years, increasing observational evidence has shown that Alfvén waves exist within interplanetary magnetic clouds (large-scale magnetic flux ropes/tubes), significantly impacting the properties and dynamic evolution of solar wind and magnetic clouds. Observations reveal inward-propagating Alfvén waves within magnetic clouds, while outward-propagating Alfvén waves dominate in the solar wind trailing edges. The decrease in Walén slope and velocity-magnetic field correlation coefficients within magnetic clouds has many causes, such as the simultaneous presence of inward- and outward-propagating Alfvén waves, occurrence of magnetic reconnection, development of thermal anisotropy, and dissipation of Alfvénic perturbations. This implies that Alfvén waves either dissipate within magnetic clouds or destroy the magnetic cloud structure. In a magnetic cloud observed by PSP in November 2018 at 0.25 au, the normalized cross helicity $|\sigma_c|$ of plasma perturbations was also low in the magnetic cloud center, consistent with the trend of decreasing Walén slope there, indicating roughly equal energy in Alfvén waves propagating parallel and anti-parallel to the mean magnetic field. In contrast, the outer layers of the magnetic cloud showed larger amplitude Alfvénic perturbations and higher $|\sigma_c|$ values, with residual energy $|\sigma_r| \sim 0$. The dissipation of Alfvénic perturbations may be connected to energy dissipation and plasma heating within magnetic clouds, though more research is needed to further clarify the relevant physical processes and mechanisms. These observational features of magnetic clouds can be linked to local processes such as solar surface source regions and their interaction with the solar wind.

Previous observational studies of Alfvén waves in magnetic clouds focused on inward (sunward) or outward (anti-sunward) propagating Alfvén waves observed by single spacecraft along the magnetic field. However, multi-spacecraft analysis of magnetic cloud (or large-scale magnetic flux tube) events reveals that magnetic clouds contain not only unidirectionally propagating Alfvén waves but also bidirectionally propagating Alfvén waves. The former may be generated by twisting of magnetic flux ropes, while the latter originate from magnetic reconnection and propagate outward along both footpoints of the magnetic cloud. The interaction between Alfvén waves may be one of the main mechanisms for energy exchange (or dissipation) during collisions of large-scale magnetic clouds. Studies of interplanetary coronal mass ejection (or magnetic cloud) collision events show that after multiple super-elastic collisions of coronal mass ejections, inward-propagating (sunward) torsional Alfvén waves appear in the interaction region and may play an important role in the transfer and dissipation of magnetic, thermal, and kinetic energy of interplanetary coronal mass ejections. In the outflow region where interchange reconnection occurs between two interplanetary magnetic flux tubes of the same polarity, large amounts of magnetic energy are continuously released and converted. The broadening of proton and electron velocity distributions along the magnetic field direction indicates plasma heating phenomena. These energized plasmas are subject to firehose instability and generate Alfvén waves during further energy conversion, partially explaining the appearance of Alfvén waves in magnetic flux tubes (or magnetic clouds).

The nonlinear cascade of low-frequency Alfvénic perturbations is one energy source for plasma heating during the non-adiabatic expansion of interplanetary coronal mass ejections. A Wind spacecraft observation of an interplanetary coronal mass ejection event at 1.0 au was later observed by Ulysses at 5.4 au. Alfvénic perturbations frequently existed within the interplanetary coronal mass ejection at 1.0 au, with an occurrence rate of 21.7% and a broad frequency range of 4×10^{-4}-5×10^{-3} Hz. When the interplanetary coronal mass ejection propagated to 5.4 au, the Alfvénicity decreased significantly, the corresponding frequency range narrowed, and the occurrence rate of Alfvénic perturbations dropped substantially to 3.0%. Meanwhile, in addition to the expansion effect of the interplanetary coronal mass ejection, the magnetic field strength in regions rich in Alfvénic perturbations also decreased considerably. The dissipation of Alfvénic perturbations can cause magnetic dissipation within interplanetary coronal mass ejections and satisfy local plasma heating requirements.

Similar results appear in statistical observational studies by Voyager 2. Statistical studies of Alfvénic perturbations within interplanetary coronal mass ejections reveal that high-Alfvénicity perturbations frequently exist within almost all interplanetary coronal mass ejections, accounting for 12.6% of all interplanetary coronal mass ejection time. As interplanetary coronal mass ejections expand and propagate outward, the time fraction of Alfvénic perturbations generally decreases linearly. The occurrence rate of Alfvénic perturbations within interplanetary coronal mass ejections is much lower than that in the surrounding background solar wind, particularly within 4.75 au. Relatively speaking, Alfvénic perturbations appear more frequently at the centers and boundaries of interplanetary coronal mass ejections. Additionally, the proton temperature within interplanetary coronal mass ejections shows a W-shaped distribution. These results indicate that Alfvénic perturbations may be closely related to plasma heating within interplanetary coronal mass ejections.

Regarding small-scale magnetic flux rope observations, PSP observations in the inner heliosphere ($\sim$ 0.2 au) have revealed small-scale magnetic flux rope events with moderate Alfvénicity, meaning these flux ropes contain Alfvén wave events. These events are also accompanied by waves with frequencies higher than the proton cyclotron frequency at the flux rope' s leading and trailing edges, which can be explained by outward-propagating ion cyclotron waves with frequencies $\sim$ 0.03–0.3 Hz and wavelengths $\sim$ 60–2000 km in the plasma rest frame.

The ubiquitous presence of Alfvén waves in the solar wind can suppress the generation of magnetic flux ropes near the Sun. Using in-situ observations from Helios and PSP, [Figure 2: see original paper] shows the variation of duration and spatial scale of small-scale magnetic flux ropes with radial distance (0.29–1 au). The number of magnetic flux ropes detected near the Sun is far fewer than at larger radial distances. Combined with observations from ACE, Wind, Ulysses, and Voyager, the radial variation characteristics of small-scale magnetic flux ropes from 0.29–8 au show the same trend. One possible reason is that these flux rope structures can be generated by local magnetohydrodynamic turbulence at larger distances from the Sun, while Alfvén waves near the Sun strongly suppress their generation. The main differences in small-scale magnetic flux rope characteristics between low and high latitudes may be attributed to Alfvén waves or Alfvénic structures, with more flux rope events at high latitudes being excluded under stricter Walén slope thresholds.

2.4 Slow Solar Wind

Alfvénic perturbations are a common feature in the solar wind, particularly in the trailing edges of fast streams. Slow solar wind generally has lower Alfvénicity, with Alfvén wave occurrence rates about half those in fast solar wind and more mixing with non-Alfvénic structures. However, this is not always the case. Under specific conditions, slow solar wind can also have high Alfvénicity (with velocity-magnetic field correlation coefficients exceeding 0.95), and this type of solar wind is called Alfvénic slow solar wind.

Observational studies show that, unlike typical slow solar wind characteristics, Alfvénic slow solar wind has low magnetic compressibility and is more similar to fast solar wind except in velocity. For example, the magnitude of plasma perturbations in Alfvénic slow solar wind is comparable to that in fast solar wind. Alfvénic slow solar wind likely originates from coronal hole boundaries, thus having typical fast solar wind characteristics. However, other studies find no significant compositional differences between high- and low-Alfvénicity slow solar wind. These two types may form due to separation of plasma and Alfvén waves originating from small coronal holes because the Alfvén speed is faster than the plasma speed, a hypothesis initially supported by simulation results. [Figure 3: see original paper] shows the propagation of plasma (purple region) and Alfvén waves (green region) originating from the same small coronal hole in a two-dimensional solar wind model in the ecliptic plane. Alfvénic slow solar wind and low-Alfvénicity slow solar wind are shown in green and purple, respectively. This model will require further statistical observational studies to verify its validity.

The Alfvénicity of plasma perturbations, whether propagating outward or inward, can be represented by σ_c, which is one of the indicators measuring the degree of velocity-magnetic field correlation. Statistical observations of Alfvénic slow solar wind show that σ_c gradually decreases with increasing radial distance, possibly due to the reduction of outward-propagating modes or the continuous generation of inward-propagating modes in flow shear regions where plasma instabilities are active. On the other hand, the decrease in σ_c is also typically associated with enhanced magnetic field or density, which reduces the Alfvénicity between velocity and magnetic field.

[Figure 4: see original paper] presents parameter distributions for Alfvénic slow solar wind, fast solar wind, and typical (non-Alfvénic) slow solar wind at 0.35 au. Similar to fast solar wind, Alfvénic slow wind has high alpha particle abundance, large proton number density flux, significant alpha-proton velocity difference, and small alpha temperature anisotropy. Although some researchers argue that at least some Alfvénic slow solar wind also originates from coronal holes, the distributions of proton radial velocity and electron temperature in Alfvénic slow solar wind are relatively close to those in typical slow solar wind, while the distributions of relative proton beam and proton temperature anisotropy show clear differences among the three solar wind types. Some studies suggest that proton beams may form from interpenetrating protons of comparable intensity generated in magnetic reconnection outflow regions and low-density beams along ion separatrices outside the outflow region. The differences in observed parameters such as velocity, mass flux, and electron temperature between Alfvénic slow solar wind and fast solar wind may be related to different magnetic field geometries in the low corona. The actual observational situation is quite complex, requiring coordinated studies involving more in-situ and imaging observations and numerical simulations to further clarify the origin of related slow solar wind and its relationship with Alfvén waves. Solar Orbiter observations of Alfvénic slow solar wind at 0.64 au show similar characteristics, making further study of Alfvénic slow solar wind observational features and identification of its solar source region extremely important for better understanding observations of this solar wind type.

Polarization analysis of Alfvénic slow solar wind reveals the presence of ion cyclotron waves and kinetic Alfvén waves, highlighting the importance of Alfvénicity at fluid scales in exciting kinetic waves. While ion cyclotron waves are mainly associated with stronger anisotropy and appear to be limited by the threshold of proton cyclotron kinetic instability, kinetic Alfvén waves have stronger magnetic compressibility, are often associated with weaker anisotropy, are constrained by the mirror mode instability threshold, and extend into the parallel firehose instability region. Some studies have pointed out that Alfvénic turbulence in the solar wind can be driven by the modulation instability formed through the nonlinear dispersion of kinetic Alfvén waves from the backward-cascading spectral branch, though the background environment studied was high-speed solar wind, and the driving mechanism of Alfvénic turbulence in slow solar wind requires further investigation. These results are helpful for theoretical studies of turbulence and dissipation in the solar wind.

Finally, the main characteristics, physical properties, origins, and effects of structures related to Alfvén waves in the solar wind environment are summarized as follows:

1. **Magnetic Field Switchbacks:** Structurally characterized by rapid polarity reversal of the radial magnetic field with deflections from a few degrees to about 180°; in Alfvénic structures, magnetic field components vary while magnetic field strength remains constant, though cases with variations in both components and strength also exist; often located in regions of locally enhanced radial velocity, frequently accompanied by Alfvénic velocity spikes. Physically, most have Alfvénic structure with no significant temperature changes and are self-similar, while a minority are compressive. They may originate near the leading edges of diverging magnetic funnels or in regions of strong solar wind plasma expansion, form through nonlinear evolution of small-amplitude Alfvén waves from the coronal base, or be rotational discontinuities formed by Alfvén waves and local magnetic flux tubes. Magnetic field switchbacks affect local magnetic field dynamics and cause negative cross helicity at smaller scales.

2. **Magnetic Field Discontinuities:** Common small-scale structures in the solar wind where magnetic field and plasma parameters change discontinuously across the discontinuity surface. Phase steepening of large-amplitude Alfvén waves propagating parallel to discontinuities energizes protons. Rotational discontinuities sometimes have structures similar to magnetic field switchbacks. Rotational discontinuities can form from switchback boundaries or Alfvén waves, while tangential discontinuities form from switchback boundaries with higher frequency. Magnetic discontinuities can accelerate jets, excite Alfvénic pulses/spikes, affect the turbulent dissipation rate of outward-propagating Alfvén waves, cause non-uniformity in magnetic field direction variations of Alfvén waves, and influence estimates of de Hoffmann-Teller frame velocity and Alfvénicity.

3. **Magnetic Flux Ropes/Tubes:** Common magnetic field structures characterized by smoothly rotating magnetic field configurations in solenoidal forms, including phenomena at different scales such as interplanetary coronal mass ejections, magnetic clouds, and small-scale magnetic flux ropes.

Interplanetary magnetic clouds contain Alfvén waves, with lower perturbation cross helicity $|\sigma_c|$ and Alfvénicity in the central region and larger amplitude Alfvénic perturbations and higher $|\sigma_c|$ in the outer layers. Alfvén wave interactions may be the main mechanism for energy exchange during magnetic cloud collisions. Small-scale magnetic flux ropes also contain Alfvén waves along with ion cyclotron waves. Magnetic flux ropes/tubes are mostly produced by solar eruptive activities, while small-scale ones can be generated by MHD turbulence. They affect the properties and dynamic evolution of solar wind and Alfvén waves, while Alfvén waves can also destroy magnetic cloud structure, suppress flux rope generation near the Sun, and wave dissipation can satisfy internal plasma heating requirements.

4. **Slow Solar Wind:** Solar wind with speeds below 500 km/s, characterized by higher proton density, lower proton temperature, higher electron temperature, and higher heavy ion charge states compared to fast wind. It typically has lower Alfvénicity, though high-Alfvénicity cases exist (Alfvénic slow solar wind) with low magnetic compressibility but large alpha particle abundance, alpha-proton velocity difference, and proton beam. σ_c decreases gradually with radial distance. Ion cyclotron waves and kinetic Alfvén waves are present. While typical slow solar wind originates near helmet streamer regions, Alfvénic slow solar wind likely comes from coronal hole boundaries or small coronal holes, with super-radial expansion reducing solar wind speed.

3. Solar Wind Turbulence

Turbulence can cascade Alfvén wave energy from large to small scales, rapidly dissipating energy and increasing the Alfvén wave dissipation rate. Solar wind turbulence dominated by Alfvénic perturbations is also called Alfvén turbulence. Its properties (such as compressibility, intermittency, anisotropy, magnetic helicity, spectral index, etc.) and evolution are not only closely related to Alfvénic perturbations and the local plasma environment but are also significantly influenced by physical processes occurring within it (such as plasma instabilities, wave reflection, excitation of counter-propagating waves, and wave-related resonant and non-resonant interaction processes), causing wave energy transfer and dissipation that correspondingly alter turbulence properties.

3.1 Physical Processes in Solar Wind Turbulence

Statistical studies of Alfvén turbulence in fast solar wind using empirical mode decomposition and Hilbert spectral analysis show that the spectra of selected events do not exhibit the anisotropy expected from critical balance theory but instead show Kolmogorov-like scaling ($E(k_\parallel) \sim k^{-5/3}$) with very weak or absent intermittency, which are distinctive features of solar wind Alfvén turbulence. High-resolution numerical simulations of reflection-driven Alfvén turbulence in fast solar wind indicate that between the coronal base and the Alfvén critical point, Alfvén turbulence cascade and dissipative heating transfer 50%-70% of the coronal base Alfvén wave power to the solar wind, while work done on the solar wind transfers only 15%-30% of the coronal base Alfvén wave power. [Figure 5: see original paper] shows the ratio of Alfvén wave heating rate to the rate at which Alfvén waves do work on solar wind per unit volume as a function of heliocentric distance, including analytical model results (green dots) and three numerical simulations under different initial conditions. The figure shows that closer to the Sun, Alfvén wave heating is more effective than work done, but beyond approximately $11R_\odot$ (where $R_\odot$ is the solar radius), Alfvén wave work becomes slightly stronger than heating, demonstrating that Alfvén wave heating and work are significantly influenced by the environment at different heliocentric distances.

Two-dimensional magnetohydrodynamic simulations of Alfvén turbulence propagating in structured, expanding solar wind, considering both fast and slow solar wind cases, self-consistently include effects such as fast-slow stream shear, compression, and rarefaction. The study finds that flow interaction greatly influences the radial evolution of Alfvén turbulence. Alfvén wave energy is depleted in velocity shear regions, accompanied by decreased normalized cross helicity, and solar wind flow compression accelerates this process. Only when both fast and slow streams exist with both compression and shear effects can a Kolmogorov-like spectrum develop.

Three-dimensional compressible MHD turbulence simulations at low Mach number reveal that both Alfvén waves and magnetosonic waves can be excited simultaneously. In magnetic pressure-dominated (low-β) cases, compressible and incompressible waves are excited, with energy primarily transferred to the Alfvén mode and relatively less to the magnetosonic mode. In plasma pressure-dominated (high-β) cases, both fast and slow magnetosonic waves exist, with no Alfvén wave characteristics found and two-dimensional turbulence carrying a large fraction of energy.

In numerical simulations of compressible MHD turbulence under uniform background magnetic fields, turbulence velocity and magnetic field are decomposed into Alfvén, slow, and fast modes using MHD wave mode polarization. Simulation results for different cross helicities, plasma β, and Alfvén Mach numbers show that the compressible component of MHD turbulence is mainly manifested as the slow mode. Both decomposed Alfvén and slow modes exhibit Kolmogorov-like power-law spectra and clear anisotropy, with wave vectors primarily perpendicular to the background magnetic field. Propagating Alfvén waves and non-propagating Alfvénic structures coexist in the incompressible perturbations of turbulence, while propagating slow magnetosonic waves and non-propagating slow-mode structures constitute the compressible component of turbulence. These results provide a new perspective for understanding compressible and incompressible perturbations in solar wind turbulence.

Using nonlinear diffusion equations in Fourier space to simulate the kinetic behavior of strong Alfvén wave turbulence from MHD to electron scales, particularly the imbalance between counter-propagating wave energies commonly observed in solar wind near the Sun. In collisionless situations, the scale where dispersion occurs is equal to or larger than the scale where dissipation acts. The combined effects of high imbalance and ion Landau damping make the magnetic energy spectrum of transverse magnetic fields steeper at sub-ion scales. This spectrum is consistent with observations in high-Alfvénicity solar wind regions (such as the trailing edges of fast solar wind) and has a shallower spectrum at shorter scales, indicating that this feature of the magnetic spectrum results from the combined influence of various solar wind streams with different degrees of imbalance.

3.2 Counter-propagating Waves in Solar Wind Turbulence

Nonlinear interactions between counter-propagating Alfvén waves can drive solar wind turbulence. The Elsässer variable z^- represents inward-propagating Alfvén waves, which nonlinearly interact with the Elsässer variable z^+ representing outward-propagating Alfvén waves, causing turbulent energy cascade and leading to decreasing Alfvénicity of solar wind perturbations with increasing heliocentric distance. Recent PSP solar wind observations show that, similar to previous results, outward-propagating Alfvén waves dominate over inward-propagating ones. The radial variation of inward perturbations is consistent with models where inward Alfvén waves are generated by large-scale gradients in Alfvén speed through reflection. Inward Alfvén waves may also form through deflection of open magnetic field lines or through non-WKB reflection that converts outward Alfvén waves into inward waves via interaction between Alfvén wave turbulence and background solar wind, while turbulence transfers momentum to the background flow.

Based on nonlinear interactions between inward- and outward-propagating Alfvén waves, Tu et al. proposed a WKB-like turbulence theory and an energy cascade dissipation model for Alfvén turbulence in the solar wind that can self-consistently explain observed variations in solar wind turbulence power spectra with heliocentric distance and proton heating phenomena in the solar wind, with theoretical results consistent with satellite observations. Building on this turbulence energy cascade model and combining it with quasi-linear theory of cyclotron waves further shows that the cyclotron resonance mechanism driven by Alfvénic perturbation cascade energy can explain observations of protons being heated perpendicular to the magnetic field while being cooled parallel to it.

[Figure 6: see original paper] shows statistical results for inward-propagating Alfvén waves in the solar wind, presenting the fraction of inward (sunward) Alfvénic fluctuation events among all Alfvénic fluctuation events observed by Wind and Voyager 2 as a function of heliocentric distance. The fraction of inward Alfvén wave events gradually increases with heliocentric distance, possibly due to generation by magnetohydrodynamic turbulence at larger distances. These inward wave variations sometimes exhibit characteristics of convective structures, particularly in high-Alfvénicity solar wind perturbations where the autocorrelation function of z^- typically shows large decreases, reaching 25%-65% of its zero-lag value. These features suggest that z^- perturbations consist of two components: high-frequency white noise and low-frequency pseudo-structures, corresponding to the flat and steep portions of the z^- power spectrum, respectively. In this case, z^- may not play an important role in the energy cascade process interacting with z^+. Compared to outward Alfvénic perturbations, inward Alfvénic perturbation events have steeper power spectra, weaker spectral intensity, and weaker anisotropy.

Analytical results from weak turbulence theory describing the nonlinear evolution of parametric instability show that if the spectrum e^+ of outward-propagating Alfvén waves along the magnetic field initially has a peak frequency f_0 (where e^+ reaches its maximum) and an infrared spectral index $-1 < p < 1$ at lower frequencies f, then e^+ has an f^{-1} scaling in the frequency range near f_0. Simultaneously, the spectrum e^- of inward-propagating Alfvén waves along the magnetic field has an f^{-2} scaling in the same frequency range.

Counter-propagating or backward-propagating perturbations in Alfvén turbulence can generate field-aligned electric fields that intermittently accelerate particles along the local mean magnetic field direction. The energy of forward- and backward-propagating Alfvén waves can be easily transferred to plasma through intermittent field-aligned electric fields on timescales much shorter than the Kolmogorov timescale of turbulence cascade. For typical solar wind turbulence parameters at 1 au, the mixing of counter-propagating waves controls energy exchange between the turbulent field and particles through non-resonant interactions of field-aligned electric fields rather than cyclotron resonance, potentially causing rapid solar wind speed variations and the resulting flattening of the velocity spectrum above 10^{-2} Hz, turbulence intensity variations/intermittency, and high reflectivity of Alfvén waves.

Furthermore, at magnetohydrodynamic scales (10–1000 s in the spacecraft frame) during the evolution of solar wind turbulence within 0.3 au, outward Alfvén modes dominate across all scales and observation distances. The fractional spectral energy density of inward fast modes decreases with distance, while the energy density ratios of both inward and outward slow modes increase with distance. Outward fast mode and inward Alfvén mode events are minority events across all distances and scales, not dominating. Outward Alfvén wave and inward slow wave events also appear in solar wind compressible turbulence, with corresponding proton velocity distributions showing bidirectional asymmetric beams: the inward beam appears for shorter durations with a narrower velocity distribution, while the outward beam has a broader distribution in the high-energy tail. This indicates that various types of wave-particle interactions (such as cyclotron resonance and Landau resonance with Alfvén and slow magnetosonic waves at kinetic scales) can collaboratively heat protons in both perpendicular and parallel directions. The characteristics of inertial-scale turbulence formed by mixing Alfvén and slow waves at proton kinetic scales can be explained by counter-propagating kinetic Alfvén wave packets or a mixture of outward-propagating kinetic Alfvén waves and kinetic slow waves.

4. Global Solar Wind Models

The Alfvén Wave Solar Model is a global model from the upper chromosphere to the corona and heliosphere that simulates three-dimensional magnetic field topology based on photospheric magnetic field data, using low-frequency Alfvén turbulence to heat the corona and accelerate the solar wind. This model does not require boundaries between open and closed magnetic fields but allows these boundaries to form and evolve self-consistently. It can simulate turbulent energy transport and dissipation, isotropic electron heating, and anisotropic proton heating, and has the capability to study physical processes including firehose instability, mirror and cyclotron kinetic instabilities, Alfvén wave reflection, and nonlinear turbulence cascade at full-solar scales.

Currently, based on the Alfvén Wave Solar Model, a series of numerical simulation studies have been conducted: (1) Compared with PSP observations during its first solar approach, the best-matching parameters are total magnetic field strength, Alfvén wave perturbation level, and parallel and perpendicular plasma β. The simulated proton temperature anisotropy is enhanced but still lower than observed values. [Figure 7: see original paper] compares the radial solar wind speed, proton number density, proton temperature, and magnetic field strength from the Alfvén Wave Solar Atmosphere Model (black lines) with OMNI observations (red lines) at Earth' s orbit. The simulation results agree well with OMNI data in radial velocity, proton density, and proton temperature, but the simulated magnetic field strength remains smaller than OMNI data most of the time. (2) Simulation results can reproduce the observed bimodal distribution of slow and fast solar wind and the relationship between solar wind speed and coronal source temperature. Compared with other types of simulations, the solar wind characteristics from the Alfvén Wave Solar Model best match observational data. (3) Simulations of slow solar wind ($< 400\ \mathrm{km\cdot s^{-1}}$) found higher charge states than in fast solar wind, supporting the hypothesis that slow wind originates from closed coronal loops and is intermittently released through reconnection. The simulations also found that coronal hole boundaries have higher electron density and temperature, causing faster ionization and giving slow solar wind from coronal hole boundaries high charge states as well, providing an alternative formation mechanism for slow solar wind with high charge states. (4) Studies of effects triggered by coronal mass ejections show that turbulent energy in coronal mass ejection sheaths and strong wave reflection regions at shocks together increase wave dissipation rates by more than 100 times, while wave energy is greatly reduced by adiabatic expansion of magnetic flux ropes. The final proton temperature anisotropy is constrained by kinetic instabilities to levels consistent with solar wind observations.

Other types of global solar wind model research have also made considerable progress, achieving results consistent with satellite observations. Considering

Alfvén wave transport and dissipation, corresponding solar wind magnetohydrodynamic numerical simulation results well reproduce the large-scale observational features of solar wind with plasma parameters (such as density, vector magnetic field, and radial velocity) similar to those observed by PSP during its first solar approach, providing greater confidence in estimating the solar wind source region at this location. When both fast and slow solar wind are introduced (including fast-slow stream shear, compression, and rarefaction effects), two-dimensional magnetohydrodynamic simulations of Alfvénic perturbations in structured, expanding solar wind find that flow interaction strongly affects the radial evolution of Alfvén turbulence, with Alfvén wave energy being depleted in velocity shear regions accompanied by decreased normalized cross helicity, a process promoted by compression effects. Some numerical simulations also consider factors such as sub-Alfvénic solar wind, background solar wind acceleration, and inhomogeneity in background density and magnetic field, achieving good results. It is worth noting that the interaction between counter-propagating Alfvén waves is one of the important mechanisms for generating Alfvén turbulence. Global solar wind models based on this mechanism require setting up physical processes that form inward-propagating Alfvén waves, one possible process being reflection caused by radial variation of Alfvén speed. Future research can further investigate the advantages and disadvantages of these different global solar wind models, learn from each other' s strengths, and combine them with the latest PSP and Solar Orbiter observations to construct a complete global solar wind model that comprehensively considers numerous effects in the solar wind. This would be extremely helpful for important research directions such as solar wind dynamics, transport and transfer of Alfvénic perturbations/turbulence in the heliosphere, and solar wind heating and acceleration.

5. Plasma Instabilities in the Solar Wind

The wide range of background solar wind plasma parameters and complex magnetic field structures may satisfy certain parameter threshold conditions, triggering corresponding plasma instabilities that excite different types of plasma waves and affect particle kinetic behavior and solar wind plasma thermodynamic properties. Below we mainly introduce research on plasma instabilities related to Alfvén waves in the solar wind, including parametric decay instability and firehose instability.

5.1 Parametric Decay Instability

In three-dimensional ideal magnetohydrodynamic simulations of solar wind turbulence, the growth rates of parametric decay instability for Alfvén waves with different amplitudes are often lower than expected from linear theory and non-turbulent cases across a wide range of background turbulence amplitudes. The density perturbations produced are consistent with characteristics of MHD slow waves and can become one of the generation mechanisms for slow waves observed in solar wind at 1 au, highlighting the influence of density variations on turbulence characteristics and solar wind plasma heating. Parametric decay instability of Alfvén waves can also excite slow waves in moderate-β heliospheric plasma sheets, with observations providing some indirect evidence. Theoretically, nonlinear interactions between Alfvén and slow waves in a broadband Alfvén wave background in the solar wind can generate Alfvén and slow waves at ion cyclotron scales.

The parametric instability process provides a filtering mechanism for Alfvén waves of different frequencies in the solar wind. Corresponding simulation studies indicate that the maximum growth rate of parametric decay instability for low-frequency ($f_0 \lesssim 10^{-4}$ Hz) Alfvén waves is suppressed by solar wind acceleration and expansion effects, while the growth rate for medium-frequency ($f_0 \approx 10^{-3.5}$ Hz) Alfvén waves is too small to show signs of parametric decay instability within 1 au, making their propagation relatively efficient. This process can explain observed trends in density perturbations and cross helicity evolution.

Most studies of Alfvén decay instability in the solar wind assume circularly polarized Alfvén waves as initial conditions. When decay instability occurs in linearly polarized Alfvén waves, unlike the circular polarization case, wave steepening provides an energy transfer channel from the mother wave to scattered waves, where nonlinear reflection can explain the observed increase with distance in the energy ratio between inward and outward Alfvénic perturbations in the solar wind. [Figure 8: see original paper] shows the energy ratio $\bar{R}(r) \equiv E_f^l/E_f^r$ of leftward (E_f^l) and rightward (E_f^r) propagating Alfvén waves as a function of heliocentric distance, where simulation results (blue line) agree with observations, mainly through the parametric decay instability process generating inward-propagating Alfvén waves to explain the observed variation characteristics of the energy ratio between inward and outward Alfvénic perturbations with heliocentric distance.

Analytical results from weak turbulence theory studying the nonlinear evolution of parametric instability in solar wind turbulence show that this instability can cause inverse cascade of Alfvén waves, with the nonlinear evolution of the instability leading to outward Alfvén wave spectra consistent with Helios observations of fast solar wind at this location (i.e., f^{-1} scaling in the $f \gtrsim 3 \times 10^{-4}$ Hz range).

5.2 Firehose Instability

In PSP observations of magnetic field switchback events, analysis of particle and plasma wave characteristics reveals that 73% of events exhibit Alfvén wave-like features with constant magnetic field strength, while the remaining 27% show compressibility with variations in both magnetic field strength and density perturbations. The boundaries of magnetic field switchbacks can be regarded as rotational or tangential discontinuities, with rotational discontinuities appearing more frequently. These observational features can be explained by firehose instability, which also serves as a candidate mechanism for switchback formation.

Magnetic field switchbacks may also be localized magnetic flux tubes corresponding to the saturated stage of firehose instability development. Analysis of magnetic and plasma perturbations related to magnetic field switchbacks shows they have characteristics of localized magnetic flux tubes with higher parallel velocity and ion β values than surrounding background plasma (likely due to hotter plasma inside the flux tubes). Magnetic field deflections before and after switchbacks indicate the presence of a total axial current concentrated in a relatively narrow boundary layer on the flux tube surface that determines the magnetic field inside the tube.

In the outflow region where interchange reconnection occurs between interplanetary magnetic flux tubes, energized plasma also exhibits firehose instability and generates Alfvén waves during further energy conversion. In these outflow regions, large amounts of magnetic energy are continuously released and converted, with broadening of proton and electron velocity distributions along the magnetic field direction indicating plasma heating phenomena.

Additionally, the Alfvén Wave Solar Model can self-consistently simulate turbulent energy transport and dissipation, electron and proton heating, and study various instability processes including firehose instability, mirror and cyclotron kinetic instabilities, and Alfvén wave reflection in full-solar-scale numerical simulations. It has been applied to numerical simulations of many macroscopic and microscopic physical processes in solar wind and solar atmosphere, and will play an important role in future studies of firehose instability in solar wind plasma.

6. Heating and Acceleration of the Solar Wind

Turbulence cascade transfers energy to small scales in the perpendicular direction, with injected energy ultimately converted into plasma thermal energy. Alfvénic perturbations are important components of solar wind turbulence and significantly impact the turbulence cascade process, becoming a non-negligible important factor in solar wind heating and acceleration. This section mainly introduces research progress on solar wind heating and acceleration related to Alfvénic perturbations to help readers understand the role of Alfvén waves in related physical processes.

In high-resolution numerical simulations of reflection-driven Alfvén turbulence in high-speed solar wind, Alfvénic perturbations transfer 50%–70% of their initial power to solar wind particles through cascade and dissipation, and only 15%–30% through work done on the solar wind from the coronal base to the Alfvén critical point. These energy transfer fractions are not fixed and depend on the photospheric boundary conditions used in the simulations.

In three-dimensional magnetohydrodynamic simulations of reflection-driven Alfvén wave turbulence, nonlinear interactions occur between outward- and inward-propagating waves. When plasma parameters such as Alfvén speed and density vary smoothly with height along flux tubes, this model cannot provide the energy needed for plasma heating and fast solar wind acceleration. However, when density perturbations exist along open magnetic fields—that is, when compressive wave effects are considered—the turbulent dissipation rate increases, thereby increasing the solar wind heating and acceleration rates.

Based on observational characteristics of plasma waves and proton velocity distributions in solar wind, it is found that under compressible conditions, outward-propagating Alfvén waves and inward-propagating slow magnetosonic waves appear with nonlinear interactions between them. Corresponding proton velocity distributions show bidirectional asymmetric beams: the sunward beam appears for shorter durations with a narrower velocity distribution, while the anti-sunward beam has a broader distribution in the high-energy tail. Protons may be heated in both parallel and perpendicular directions through various types of wave-particle interactions (such as cyclotron resonance and Landau resonance with these two waves).

Three-dimensional hybrid simulations of the evolution of circularly polarized Alfvén wave parametric decay instability in low-β plasma turbulence show that compared with linear Vlasov theory results, the damping rate of ion-acoustic modes produced by the instability process decreases, but Landau damping of ion-acoustic waves can heat ions parallel to the background magnetic field. In such low-β turbulent plasma, parametric decay instability is an important energy dissipation pathway for low-frequency Alfvén waves at scales much larger than ion kinetic scales.

The Alfvén Wave Solar Model can simulate energy transport and dissipation processes in solar wind turbulence and the different heating characteristics of electrons and protons, including particle acceleration and heating in physical processes that are difficult to handle in analytical theoretical studies, such as firehose instability, mirror and cyclotron kinetic instabilities, and Alfvén wave reflection. Simulation results can be compared with actual solar wind observations, and based on this comparison, the model can be modified and improved to make simulation results more consistent with in-situ solar wind observations, especially those from PSP and Solar Orbiter in the inner heliosphere, to further clarify the role of Alfvén wave-related dissipation processes in heating different particle species and accelerating the solar wind.

Finally, [Figure 9: see original paper] shows observations of an interplanetary coronal mass ejection by Wind at 1 au and Ulysses at 5.4 au, including magnetic field strength, proton number density, solar wind speed, ratio of observed to expected temperature, and the parameter E_{rr} representing Alfvénicity. Regions rich in Alfvénic perturbations are indicated in sky blue, while regions with fewer Alfvénic perturbations are shown in light pink. The figure shows that Alfvénic perturbations are also commonly observed within interplanetary coronal mass ejections. At 1.0 au, the turbulence cascade rate in Alfvénic perturbation-rich regions is much greater than in regions with low Alfvénic perturbation occurrence rates, satisfying local plasma heating requirements. In regions with low Alfvénic perturbation occurrence rates, the turbulence cascade rate remains stable even when magnetic field strength decreases. Thus, dissipation of Alfvénic perturbations can cause magnetic dissipation and local plasma heating within interplanetary coronal mass ejections.

7. Summary and Outlook

As a wave mode that exists in large quantities in the solar wind, Alfvén waves are closely related to magnetic field switchbacks, magnetic discontinuities, magnetic flux ropes/tubes, and slow solar wind. They not only affect the dynamic properties of plasma but also, under specific threshold conditions, cause particle energization or plasma heating through processes such as parametric decay instability, firehose instability, reflection, and nonlinear cascade, influencing the lifetimes of these structures. In solar wind turbulence dominated by Alfvén waves, Alfvénic perturbations or other wave modes cause particle energization through physical processes including plasma instabilities, wave reflection, excitation of counter-propagating waves, and wave-related resonant and non-resonant interactions, further affecting turbulence properties (such as compressibility, intermittency, anisotropy, magnetic helicity, and spectral index). The Alfvén Wave Solar Model—a global model that heats the corona and accelerates solar wind based on low-frequency Alfvén turbulence—can self-consistently simulate turbulent energy transport and dissipation, electron and proton heating, and study physical processes including firehose instability, mirror and cyclotron kinetic instabilities, Alfvén wave reflection, and nonlinear turbulence cascade in full-solar-scale numerical simulations.

The above observational, theoretical, and simulation studies related to Alfvén waves in the solar wind have made considerable progress, highlighting the importance of Alfvén waves/perturbations in related phenomena and physical processes. With increasing perihelion observation data from PSP and Solar Orbiter, future research on Alfvén waves in the solar wind can focus on the following five aspects:

First, studies of sub-Alfvénic solar wind properties in the inner heliosphere and their relationships with turbulence, perturbation anisotropy, intermittency, magnetic field switchbacks, and other Alfvén wave-related phenomena, clarifying the role of Alfvén waves.

Second, continuous improvement and refinement of global solar wind models (such as the Alfvén Wave Solar Model) using the latest observational data, particularly improving the accuracy of magnetic field extrapolation methods. Simultaneously, clarifying the advantages and disadvantages of different global solar wind models, learning from each other’ s strengths, and combining them with the latest observations to construct a comprehensive global model that considers numerous effects in the solar wind would be extremely helpful for important research directions such as solar wind dynamics, transport and transfer of Alfvénic perturbations/turbulence in the heliosphere, and solar wind heating and acceleration.

Third, connecting inner heliosphere Alfvén wave/perturbation events with possible solar source regions requires not only combining in-situ observations with remote sensing imaging data but also relying on more accurate global solar wind models. This is closely related to the origin problem of solar wind.

Fourth, on the theoretical research side, under the observational background conditions of Alfvén waves in the solar wind and combined with the latest PSP and Solar Orbiter observations, developing quantitative or semi-quantitative methods for wave dissipation mechanisms to compare with actual observations is an important research direction. Wave dissipation mechanisms also involve kinetic processes of plasma instabilities (such as parametric decay instability and firehose instability) and wave-particle interactions. Strengthening connections with observations, such as heating and particle dynamic behaviors associated with phenomena like magnetic field switchbacks, magnetic flux tubes, and Alfvénic pulses/spikes, is also an indispensable research aspect. In this direction, studies of kinetic wave modes and plasma instability processes in Alfvénic slow solar wind cover the aforementioned theoretical content and help understand the properties and energy dissipation of slow solar wind. Solving these specific problems also contributes to improving and refining global solar wind models to address current inconsistencies between model results and some observations.

Finally, numerical simulation studies of Alfvén waves in the solar wind are valuable for understanding the aforementioned four aspects. They not only help address nonlinear and non-uniform problems that are difficult to handle theoretically but also allow direct comparison between simulation results and observations. Future developments can draw on theoretical research results to develop new simulation methods, such as: (1) Simulating processes from dissipation scales (particle scales) to injection regions to help understand key issues like Alfvén turbulence dissipation and plasma heating; (2) Simulating Alfvénic slow solar wind to clarify its connections and differences with other fast and slow solar winds and confirm its source region; (3) Conducting simulation studies of solar wind magnetic field switchbacks to clarify their relationship with Alfvén waves and their role in various solar wind processes; (4) Simulating Alfvén wave propagation and interaction in magnetic flux tubes, including plasma heating and acceleration processes and plasma wave excitation, with results applicable to interplanetary and solar atmospheric environments.

Research on these five aspects still has a long way to go. It is hoped that more new observation data from PSP, Solar Orbiter, the Advanced Space-based Solar Observatory (ASO-S), and other inner heliosphere satellites will provide richer and more detailed information to advance related research, reveal more observational features and evolution processes of Alfvén waves in the solar wind, their relationships and interactions with structures at different scales, and their role in solar wind acceleration and heating processes.

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