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Alfvén Waves in the Solar Wind

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Abstract Alfvén waves are found to be ubiquitous in the solar wind. Recent progress in observational studies of the waves is reviewed to formulate a microscopic picture for the Alfvénic fluctuations. The main aspects of the observational properties of these waves, including the wave intervals, propagation, evolution, origin and generation, are presented. Then Alfvén wave heating and acceleration of the solar wind plasma are briefly introduced. The relation of the waves to rotational and tangential discontinuities, magnetic decreases, and other relatively large-scale structures such as flux tubes/ropes, magnetic clouds and interplanetary coronal mass ejections in the solar wind is particularly investigated. Finally, some remaining open questions are also indicated due to their fundamental importance of understanding of the physical nature of Alfvén waves and the role of the waves in heating and accelerating the solar wind.

Key words Alfvén wave, Solar wind, Rotational Discontinuity (RD), Tangential Discontinuity (TD), Solar wind structures

Classified Index P 353

1 Introduction

The interplanetary medium provides an excellent example of an astrophysical plasma where Magnetohydrodynamic (MHD) waves can be studied in situ with instruments considerably smaller than the Debye length. Knowledge of the detailed wave structure is very important in understanding energetic particle propagation within the solar wind. Now Alfvén waves[1] are perhaps the most fascinating and intriguing wave mode attracting a great deal of interest in space and solar physics, and can make a significant contribution to microscale (about several hours or less) fluctuations in the solar wind at 1 AU[2−4] and to some heliospheric processes. For example, in the solar wind, most of the energy of fluctuations has a clear Alfvénic nature[5], affecting the access of galactic cosmic rays to near-Sun regions and the generation and propagation of energetic particles in the heliosphere[6]. The dispersive, dissipative and compressive features of these nonlinear Alfvén waves may be important for the heating and acceleration of the solar wind[7].

In the solar wind, there is no obvious evidence for magneto-acoustic wave modes that are either more strongly damped or less strongly generated than Alfvén waves[8−9], and if identified, will have small average power of the order of 10% or less of that in

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Alfvén waves[4]. This is mainly because an Alfvén wave is only slightly damped. It is characterized by constant pressure, density, and magnetic field strength and by velocity and magnetic field fluctuations, $\boldsymbol{v}$ and $\boldsymbol{B}$, that are perpendicular to both the background magnetic field $\boldsymbol{B}_0$ and wave vector $\boldsymbol{k}$. The two fluctuations are connected by the Walén relation[10−11]

$$\boldsymbol{v} = \pm A \frac{\boldsymbol{B}}{\sqrt{\mu_0 \rho}}, \tag{1}$$

where the anisotropy parameter

$$A = \sqrt{1 + \mu_0 (P_\perp - P_\parallel)/B^2},$$

$\pm$ denotes the sign of $-\boldsymbol{k} \cdot \boldsymbol{B}_0$ (*i.e.*, $\boldsymbol{B}$ is antiparallel to $\boldsymbol{v}$ if the angle between $\boldsymbol{k}$ and $\boldsymbol{B}_0$ is acute), ρ is the plasma mass density, μ_0 is the permeability of free space, $P_\perp$ and $P_\parallel$ are the plasma pressure perpendicular and parallel to $\boldsymbol{B}_0$, respectively. In the solar wind, the influence of the thermal anisotropy is often not important and can be ignored, so we usually take $A = 1$. The relation (1) is often used to identify Alfvén waves in the solar wind, and will be discussed further in Section 4.2.

1.1 Early Observations

During Mariner 2 flight to Venus in 1962, the statistical properties of observed magnetic field and plasma velocity variations indicated some Alfvén and/or fast wave-like phenomena in the interplanetary space[2,12], but Coleman[2] pointed out that these results did not indicate whether Alfvén waves were definitely present. In 1968, Unti and Neugebauer[3] examined several segments of the radial component of the same velocity and magnetic field data, and found explicit evidence for Alfvén wave but not for magnetosonic waves, which is in agreement with Barnes' theory[13] that an Alfvén wave is not strongly damped in a moderate or high β plasma. The wave has an oscillatory structure with a period of 10~20 min and a nearly constant density.

Case studies on Mariner 5 data[8] clearly showed the existence of large amplitude, aperiodic Alfvén waves, propagating outward from the Sun along the average magnetic field direction and dominating the fluctuations at least 30% of the time, based on the striking correlations (see Walén relation (1)) between the radial components of the plasma velocity and the magnetic field in the solar wind.

As far as the correlations between the plasma velocity and the magnetic field fluctuations are concerned, Alfvén waves had previously been identified with one-dimensional data by Coleman[2,12,14], Unti and Neugebauer[3], and Belcher *et al.*[8]. Belcher and Davis[4] firstly used three-dimensional vector measurements to illustrate these high correlations, the most fundamental characteristic of Alfvén waves, and similar methods were adopted by many subsequent researchers[9,15−16].

Most of these early observations were made by only one single spacecraft, but Denskat and Burlaga[15] supplemented the results of Burlaga and Turner[17] using the measurements of two Explorer satellites and the statistics on three-dimensional velocity-magnetic field correlations. Such multispacecraft observations are very few[18−19], and need further investigation to get more accurate information on Alfvén waves than before.

1.2 Wave and Turbulence Descriptions

The study of the solar wind fluctuations can be classified into two main areas: a turbulence description suggested by Coleman[20] and an Alfvén wave description by Belcher and Davis[4]. Both have met with a good deal of success in explaining the related observations, but still face notable difficulties. On the one hand, classical turbulence, by its very definition, is unable to account for well-ordered structures observed in the plasma and field variables on different temporal scales[21] and for no direct interactions between outward propagating Alfvén waves[22−23] because turbulence usually involves the couplings between fluctuations at very different scales[24] and in different directions[25]. And a linear superposition of Alfvén waves and convective magnetic structures (or 2D turbulence) was proposed to reconcile the two descriptions (*e.g.*, Matthaeus *et al.*[26], Tu and Marsch[27], and citations therein), which may not work well for small-scale Alfvénic fluctuations. On the other hand, the wave description could not resolve the question of the formation of the power-law spectrum of the magnetic field fluctuations in the solar wind[20−23], which may be created only by nonlinear turbulent processes[28].

In this paper, the wave language is used to discuss the the microscale (a few hours or less) solar wind fluctuations for its simplicity and conceptual clarity. For a turbulence description, interested readers are referred to relevant reviews by Barnes[29], Tu and Marsch[28], Goldstein *et al.*[30], Velli and Pruneti[31], Bruno and Carbone[32], and Bruno *et al.*[5]. Two terms, "Alfvén waves" and "Alfvénic fluctuations", have different meanings, which should be clearly stated as follows.

The term Alfvén wave was used by Denskat and Burlaga[15] to describe propagating fluctuations satisfying the Walén relation (Eq.(1)). Many authors[2−4,8,12,14,20] have studied the solar wind fluctuations approximately satisfying the Walén relation (1). Denskat and Burlaga[15] mentioned that Eq.(1) can also describe some nonpropagating fluctuations, so the Walén relation alone is not sufficient to identify Alfvén waves. Moreover, Alfvén waves observed in the solar wind are not necessarily periodic similar to a monochromatic wave and may simply be propagating fluctuations in the solar wind[24]. Belcher and Davis[4] mentioned that the Alfvén wave description can explain all the observed properties in a straight forward manner with only one condition that all the waves should propagate away from the Sun. This condition is largely consistent with the high-speed solar wind observations. Therefore we will use the term "Alfvén wave" to describe those aperiodic (nonperiodic) and nonsinusoidal fluctuations in the solar wind.

The term "Alfvénic fluctuations" was used by Burlaga[33] to describe the fluctuations to some degree consistent with the theory of Alfvén waves, that is, they are not pure Alfvén waves. Hence the two terms will be used to describe the solar wind fluctuations in the sense of the degree of their Alfvénicity, a measure of the correlation between the velocity and magnetic field fluctuations, which is an important topic to be discussed in Section 2.4.

Early observations of Alfvén waves in the solar wind and their properties have been reviewed by Burlaga[34], Völk[35], and Barnes[29]. The present paper does not aim to be exhaustive and fully comprehensive, but rather to draw on pertinent literature in an illustrative manner, and so largely omits the studies included in the thoroughly conducted previous reviews. It wishes to highlight recent progress in observational studies of Alfvén waves in the solar wind and unresolved questions of interest for future studies.

2 Properties of Observed Alfvén Waves

Large-amplitude Alfvén waves are often present in the high-speed solar wind streams, with transverse fluctuations comparable to or larger than the field magnitude[36]. They may be plane Alfvén waves that can exist with arbitrarily large amplitudes[37], in which case the magnetic field magnitude is still constant and the dispersion relation and the direction of the energy flux remain the same as those in the small-amplitude case[38−39]. These Alfvén waves are strictly undamped in a uniform collisionless plasma, but the magnetoacoustic wave suffers Landau damping[13], which may explain the relative lack of shocks and magnetoacoustic waves in the solar wind.

Belcher and Davis[4] conducted an extensive study of the microscale fluctuations (about 1 hour or less) using plasma and magnetic field data from Mariner 5, and found that (1) large-amplitude, nonsinusoidal Alfvén waves propagating outward from the sun with a broad wavelength range from 10^3 to 5×10^6 km are dominant in the microscale structures at least 50% of the time; (2) the purest Alfvén waves occur on the trailing edges (where the velocity decreases slowly with time) of high-speed solar wind streams, but in low-speed streams Alfvén waves generally have smaller amplitudes than those in the fast streams and tend to be less Alfvénic in the sense that they may be mixed with non-Alfvénic structures possibly with a static nature; (3) the largest amplitude Alfvénic fluctuations appear in the compression regions on the leading edges (where the velocity increases rapidly with time) of high-speed streams. This early work laid the groundwork for the field of Alfvén waves in the solar wind.

Denskat and Burlaga[15] pointed out two general classes of Alfvén waves, *i.e.*, those with and without the condition of constant magnetic field strength. First, in the case with constant magnetic field strength, Alfvén waves are transverse waves[39], or plane-polarized waves[40], which was found rarely[17] due to measurable fluctuations in the field strength in most of the event interval. Second, in the case without constant magnetic field strength, such Alfvén waves are theoretically interpreted as a kind of nonlinear, linearly polarized ones[39], which seems to contradict the observations of large-amplitude Alfvén waves in the solar wind[4,8,23].

Gosling *et al.*[41] summarized discrete types of Alfvén waves in the solar wind: (1) arc-polarized waves whose magnetic field vector rotates along an arc transverse to the minimum variance direction for the magnetic field[21], (2) torsional Alfvén waves in magnetic flux ropes[42], (3) limited events of candidate solitary waves identified in Ulysses data[43], and (4) Alfvénic disturbances propagating in opposite directions along with plasma jets produced by magnetic reconnection in the solar wind[44]. We will discuss the various properties of these waves and their relation to some structures in the solar wind respectively and carefully in the following sections.

The above brief overview covers the main aspects of the properties of Alfvén waves in the solar wind. The following sections will be devoted to further detailed information on the wave intervals, propagation, evolution, origin and generation, and other related topics.

2.1 Alfvénic Intervals

Periods with a high correlation of velocity and magnetic field data in the solar wind are termed "Alfvénic intervals"[9] and have been extensively studied by many researchers[3,17,22,45−48].

Mariner 5 observations[8] clearly showed that large-amplitude Alfvén waves dominate the solar wind fluctuations at least 30% of the time. Similar results were also obtained from Explorer 43 and Ulysses data[17,36]. But Denskat and Burlaga[15] found that Alfvén waves are only 12% of the time from the Explorer 33 and 35 measurements, and Riley *et al.*[21] also found that arc-polarized (well-ordered rotations of the magnetic field) Alfvén waves only account for about 5% to 10% of the total data set based on a statistical examination of the Ulysses data in the ecliptic plane, both of which are consistent with the conclusion that highly pure Alfvénic fluctuations are rare based on Voyager observations[9].

The percentage of the Alfvén wave interval in the solar wind may vary with different locations of spacecraft, various solar activity levels, and different event selection criteria by authors. For example, the Helios spacecraft observations showed that about 75% of the interval is characterized by Alfvén waves[49], based on a criterion less strict than that (the normalized cross helicity $\sigma_{\rm c} > 0.8$, as a measure of Alfvénicity) used by Roberts *et al.*[9], who found only about 22% of the time at the 3-hour scale from the Helios 1 observations, implying that for about 78% of this interval there exist fluctuations probably not generated in the solar atmosphere[50]. There are also many times when no Alfvén waves can be identified in the solar wind[4].

The percentage of Alfvénic intervals, on average around 30%, increases obviously near the Sun, and fewer Alfvénic intervals ($< 1\%$) exhibit an inward sense of the wave propagation[51]. However, near 1 AU at most 15% of the hourly solar wind fluctuations are purely Alfvénic and also propagate outward from the Sun[9]. This shows a tendency for a decreasing contribution of Alfvén waves to the solar wind fluctuations with the increasing radial distance from the Sun.

In most of the events mentioned here, it is clear that the correlations of velocity and magnetic field are not perfect, and the magnitude fluctuations were nearly always present. The nature of the Alfvénic fluctuations was still not fully understood, and fast modes and/or complex static structures could be taken into account[17].

2.2 Wave Propagation Direction

The frequent presence of outward propagating Alfvén waves was identified by many in situ observations of the solar wind fluctuations[8,17,21,52−53], that is to say, most of the waves are moving away from the Sun. On the other hand, a statistical study[9] showed that inward propagating Alfvén waves are more likely to appear with increasing heliocentric distance, indicating that local generation must also occur, and the solar wind cannot be in a static state of superposed Alfvén waves. Oppositely propagating Alfvén waves can be produced through the scattering of the waves by static structures in the solar wind[27].

A recent case study of the solar wind fluctuations at 1 AU[41,54] reconfirmed the rare existence of discrete, inward propagating Alfvén waves, associated with special events such as magnetic reconnection exhausts and/or backstreaming ions from reverse shocks. Further analysis and detailed modeling of these processes should be a future topic of research.

Meanwhile, the background magnetic field $\boldsymbol{B}_0$ is very important for the wave propagation direction and usually obtained by the average direction or minimum variance direction of the magnetic field fluctuations. It is plausible that all Alfvén waves propagate parallel to $\boldsymbol{B}_0$[8], which is supported by many studies on in situ observations of Alfvén waves in solar wind[4,15,17,52,55]. But a statistical analysis[21] of Ulysses data in the ecliptic plane indicated that the minimum variance direction associated with Alfvén waves is highly oblique to the average magnetic field $\langle \boldsymbol{B} \rangle$, while the intermediate variance direction is roughly along this direction. So a question arises as to whether the average direction or minimum variance direction of the magnetic field can be regarded as $\boldsymbol{B}_0$, which will be illustrated in Section 2.3.

In addition, some observations of Alfvén waves in the solar wind[19,56−58] showed a propagation tendency of the waves toward the radial direction rather than the field direction, which conflicts with an Alfvén wave interpretation. Moreover, the gradients due to streams should turn the wave vector $\boldsymbol{k}$ toward $\boldsymbol{B}_0$ in trailing edges of the streams and away from $\boldsymbol{B}_0$ in leading edges[59], which is not confirmed by observations[17]. But multispacecraft observations of microscale fluctuations in the solar wind indicated that a different class of Alfvén waves propagate almost perpendicular to the mean field, and most Alfvénic waves propagate neither radially nor along the mean field away from the Sun[15].

In a word, the propagation direction of Alfvén waves in the solar wind may be complicated by the fact that Alfvén waves have different origins and various generation processes. Convective structures and high- and low-speed stream interactions could also change the propagation direction. To get a more accurate propagation direction of an Alfvén wave, much care should be taken when analyzing the plasma and magnetic field data, and new data processing techniques are required.

2.3 Background Magnetic Field

Mean value of the magnetic field is usually assumed to be the background magnetic field $\boldsymbol{B}_0$[60], which is not an observable quantity[21,61] or easily determined[42]. It is very possible that the average field $\langle \boldsymbol{B} \rangle$ cannot define the direction of $\boldsymbol{B}_0$. Lyu and Kan[62] concluded that it is not necessary for the local average magnetic field to be in the same direction as the ambient magnetic field. As mentioned in Section 2.2, Riley *et al.*[21] deduced that under certain model assumptions, $\langle \boldsymbol{B} \rangle$ can be nearly perpendicular to $\boldsymbol{B}_0$.

Recent Advanced Composition Explorer (ACE) observations of Alfvén waves showed that the fluctuations are relative to a slowly varying base value rather than to an average value[54], implying that it is not appropriate for us to always take the average value of the magnetic field to be the background, though most previous studies often do[28,30,63−64] (and references therein). Obviously, those previous results based on statistical analyses of the solar wind fluctuations may need to be reexamined.

It is difficult to select suitable time intervals over which the averages should be taken. The wave period varies from several minutes to a few hours[4,19,65]. Even one hour magnetic field averages may not smooth out most wave effects on the solar wind fluctuations[19]. A similar difficulty also arises in the studies of the solar wind discontinuities[66].

Although the minimum variance direction of magnetic fields is observed to be aligned with the mean field direction $\boldsymbol{B}_0$[45,65,67−70], it is still problematic to determine $\boldsymbol{B}_0$ from Minimum Variance Analysis (MVA) of the magnetic field. For ideal Alfvén waves, no correlation would be expected between the velocity and magnetic field fluctuations along the minimum variance direction, but in fact a weak correlation (the coefficient is equal to 0.55) exists[71]. Although this could be related to a temporal change in the ambient magnetic field direction along which the waves were propagating, we cannot exclude the possibility that the minimum variance method cannot give an acceptably accurate estimate of the propagation direction of Alfvénic fluctuations[15,72].

Now we are trying new methods to obtain the directions of the background magnetic field and of the wave propagation more accurately than before.

2.4 Solar Wind Alfvénicity

The solar wind Alfvénicity describe to what extent the fluctuations are purely Alfvénic, and can be measured by several different parameters, such as the Walén slope (slope of the Walén regression line from the relation (1)), the normalized cross helicity $\sigma_{\rm c}$[9], or the velocity-magnetic field correlation coefficient. The case of $|\sigma_{\rm c}| \approx 1$ shows the appearance of highly Alfvénic fluctuations, so do the other two parameters.

The Alfvénicity may depend on the observation locations in the solar wind. Although Alfvén waves in compression regions are not quite as pure as those identified in the trailing edges of high-speed streams[4], both high and low values of cross helicity were found in various solar wind conditions[23,47−48,50,73−74], and the walén slope varies widely from 0.28 to 0.93 at 1 AU[41]. Near the Sun purest Alfvénic fluctuations are found in regions with small velocity gradients[50] rather than in the trailing edges of high-speed streams[4]. In fast polar solar wind region, the Alfvénicity, denoted by the correlation of the magnetic field and velocity components, decreases with increasing solar distance[71], which hints at the possible evolution of Alfvén waves.

The properties of the solar fluctuations in the inner heliosphere (0.3 to 1.0 AU) were found to depend dramatically upon the time scale[9−51]. For short scales (1∼12 hours) Alfvénic correlation is dominant, which is most obvious near the Sun in the initial and central parts of the trailing edge of high-speed streams, as found by previous studies in the solar wind. But for long scales (0.5 to 3 days) no systematic Alfvénicity exists, while compressive variations (positively correlated magnetic and thermal pressure) become dominant.

There are various reasons for the low degree of the solar wind Alfvénicity. Burlaga and Turner[17] believed that the Explorer 43 observations of Alfvén waves are not pure transverse Alfvén waves due to accompanied nonzero fluctuations in the magnetic field magnitude ($\delta\boldsymbol{B}/\bar{B} \approx 0.06$). In the case of relatively low correlation coefficients ($|\rho| \leqslant 0.8$), there may be a mixture of Alfvén and magnetoacoustic modes, or mixture of different propagation directions of Alfvén modes, or a superposition of static structures, all of which make the mode identification more difficult[8]. Furthermore, a strong interaction between the longest-wavelength fluctuations and the large scale solar wind structures is expected by Bruno *et al.*[65], which, with increasing heliocentric distances, may cause the gradual loss of the Alfvénicity of the lowest-frequency fluctuations. It is clear that the way these fluctuations interact with the ambient solar wind depends on their frequency range during their outward propagation. There are no clear answers to this question since complex dynamics and structures characterize most in situ solar wind observations.

Roberts *et al.*[50] suggested that a perfectly pure Alfvén wave is not likely to have $|\sigma_c| < 0.8$ within measurement errors from high accuracy of the plasma and field data, which is a more restrictive and more physically motivated criterion for Alfvénic fluctuations than that used previously[4]. Studies on such a high degree of Alfvénicity[23] can be completed by analyzing high resolution plasma and magnetic field data, which may provide some new aspects of Alfvén waves.

2.5 Wave Superposition

In the solar wind, the correlated velocity and magnetic field fluctuations might be a superposition of many small-amplitude Alfvén waves with different frequencies and different wave numbers[27,75–76]. But in a Corotating Interaction Region (CIR), relatively stable, large-amplitude Alfvén waves were observed by Pioneer 11 and 10 at 2.5 and 5.0 AU, with the higher frequency waves superimposed upon the lower frequency ones[19]. When modeling such microscale fluctuations, large-amplitude or nonlinear effects should be taken into account.

It was shown that purely outward propagating Alfvén waves alone do not interact nonlinearly with each other, and the spectrum shape of the waves could not change with increasing heliocentric distance[22,45]. In theoretical studies, nonlinear interactions among these Alfvén waves are often ignored[77].

But forward and backward propagating Alfvén waves could interact to generate both static Pressure-Balanced Structures (PBSs) and homogeneous Alfvén waves at second order[78]. Density and magnetic field magnitude fluctuations inside 1 AU indicate the anti-correlation characteristic of PBSs, a static structure convected by the solar wind[8] and previously found in the outer heliosphere[50]. Further, nonlinear Alfvén waves traveling in different directions but with equal group velocity were investigated by a second-order analysis of a MHD model and hybrid simulations[79], and can produce PBSs with wave vectors perpendicular to the background magnetic field and homogeneous fast waves with constant density and magnetic field magnitude to second order.

There are still no definite answers to the basic question whether the Alfvénic fluctuations could be described by a superposition of noninteracting Alfvén waves or a spectrum of turbulent fluctuations with a cascade of energy to small wavelengths[28,80–81]. More detailed observations should be made to provide new insight into this question.

2.6 Wave Evolution

Since the observed Alfvén waves may be used as a useful tool for probing the processes at the sun[82–83], and may have important contributions to the dynamics of the solar wind[84–87] and cosmic rays[88–90], it is important to study the wave evolution in the solar wind at all heliocentric distances[4,50,91].

With increasing heliocentric distance away from the Sun, it was found that the Alfvén wave period becomes shorter[65], and that both the normalized cross helicity and the Alfvén ratio decrease[9,47,50,65,74,92–98], which indicates an evolution toward a less purely Alfvénic state in the outer heliosphere. The decreases may be the result of gradual increase of the inward propagating Alfvén waves[9,50] and the propagation of Alfvén waves in the radially expanding solar wind[75,91]. To explain the radial evolution of the high-speed solar wind fluctuations, Tu and Marsch[27] presented a two-component fluctuation (Alfvén waves and convective static magnetic structures) model, but more supporting details are still needed for these microscale Alfvénic fluctuations. Some difficulties still exist in the interpretation of the fluctuation evolution, and related discussions can be found in Tu and Marsch[27].

The radial evolution of the wave amplitudes was examined by Villante[18] using the Helios 1 and Helios 2 spacecraft observations of a stream front, and might agree better with saturated waves than undamped ones between 0.41 and 0.65 AU. The result would imply that the contribution of the Alfvénic fluctuations to the energetics of the solar wind expansion may be significantly larger than that was previously calculated.

In the polar wind, previous analyses of Ulysses data[99−100] have shown that the properties of Alfvénic fluctuations appear to be determined by the heliocentric (or radial) distance rather than the heliographic latitude. Bavassano *et al.*[6] examined the radial evolution of outward and inward hourly-scale Alfvénic fluctuations in the polar wind, and found that different radial regimes emerge at different heliocentric/radial distances. At distances smaller than 2.5 AU the large outward fluctuations decrease faster than the small inward ones, but beyond 2.5 AU the radial gradient of the inward fluctuations becomes steeper and steeper than that of outward ones. Both fluctuations decrease at almost the same rate. The new behavior of outward and inward Alfvénic fluctuations imposes a constraint on theoretical models for wave/turbulence evolution in the solar polar wind.

The wave evolution also has an intimate connection with its origin at or near the Sun. Using hour-averaged data from the Helios and Voyager spacecraft, Roberts *et al.*[50] investigated the origin and evolution of low-frequency interplanetary fluctuations from 0.3 to 20 AU, and found that temporal scales longer than the transit time (from the Sun to the spacecraft) with a high correlation between velocity and magnetic field fluctuations indicate a solar origin for the initial outward propagating Alfvén waves. The solar origin of Alfvén waves and associated generation mechanisms will be discussed in Section 2.7.

2.7 Origin and Generation

Most results of many observational studies[4,24,50] support the view that the vast majority of outward propagating Alfvén waves are possibly the undamped remnants of waves generated at or near the Sun, and that the related dynamical evolution, probably including shear-generated nonlinear couplings[20] and the interaction between waves and different structures, is important at all heliocentric distances.

Significant variations in the velocities, densities, and temperatures of protons and α-particles in high-speed streams were found[60], and become more evident near the Sun between 0.3 and 0.7 AU than at 1 AU. These variations are thought to be related to various flow tubes originating in the coronal holes on the Sun (*e.g.*, supergranulation cells). As pure Alfvén waves are often observed in high-speed streams[4], it is natural to postulate the solar origin of Alfvén waves.

Many theoretical and numerical simulation studies were carried out on the problem how Alfvén waves are generated to propagate outward from the Sun. Here we just mention several generation mechanisms associated with the solar wind observations in the following.

The ACE observations of a quasi-stationary reconnection[44] showed that Alfvén waves propagating along the reconnected field lines bound a Petschek-type reconnection exhaust region. Then MHD simulations of magnetic reconnection[101] showed that Alfvén waves are generated at the reconnection point and propagate along the reconnected field line, carrying about 30% or more of the released magnetic energy in a wide range of plasma β (ratio of plasma to magnetic pressure). This result is expected to have important implications for the wave generation and the acceleration of the high-speed solar wind.

Another possible mechanism, in the solar wind, is stream shear because it is one of the most natural sources for generating fluctuations besides compression[50]. The former may play a more important role in the generation process than the latter, because large values of stream shear in interaction regions can be strong enough to prevent the steepening of compressions[102].

It should be pointed out that the majority of the solar wind fluctuations at daily scale appear to be progressively produced not by any direct solar contribution but through dynamical processes acting during the wind expansion in the interplanetary space[51].

Both observational and theoretical efforts are needed to better understand these various wave generation processes.

2.8 Surface and Pulsed Alfvén Waves

It was proposed[103−105] that MVA of Tangential Discontinuities (TDs) often detects surface Alfvén waves[72], which can travel along plane and filamentary structures (*e.g.*, discontinuities) in both interplanetary and interstellar space[106], and can couple to kinetic Alfvén waves leading to dissipation of the surface waves and heating of the surface[107−108]. The model of surface Alfvén waves on a TD[72,105] could explain the observed alignment of the changes in velocity and magnetic field vector across the TD and the subunity Walén slope ($R_{\rm VB} < 1$) if the waves travel both inward and outward along the TD. But Uberoi[109] showed theoretically the existence of Alfvén surface waves in low-β plasma conditions (*e.g.*, solar corona), which may be not applicable for the general case of the solar wind.

Pulsed Alfvén waves in the solar wind were reported by Gosling *et al.*[41]. These waves have approximately plane-polarized rotations ($6^\circ \sim 109^\circ$) in the magnetic field and velocity vectors away from the directions of the underlying field and velocity and then back again. They believed that such wave phenomena are pervasive (about 17.5 events per day) in the full range of solar wind speeds ($320{\sim}550\,\rm km{\cdot}s^{-1}$), and are probably solitary waves. Such solitary waves might play an important role in heating and accelerating the solar wind, especially close to the Sun[110−111]. Now it is uncertain where are the pulsed Alfvén waves originated, although they may be produced by the evolution of Alfvénic turbulence[41]. Pertinent observational evidence should be presented for the solitary Alfvén waves in the solar wind, and theoretical studies of the wave properties are also in great need of better understanding.

3 Alfvén Wave Heating and Acceleration

In this section, we will introduce some relevant results on the Alfvén wave heating and acceleration of the solar wind plasma. The Alfvén wave contribution to the energetics of the corona and solar wind has been considered since its discovery nearly a half century ago[3,8,20,85]. At heliocentric distance $r \geqslant 0.3\,\rm AU$, the power spectrum of the solar wind magnetic fluctuations are dominated by low-frequency ($0.001{\sim}0.1\,\rm Hz$) Alfvén waves that were demonstrated to transport a significant outward momentum to the solar wind particles[85,111−112] and to create an additional pressure to accelerate the solar wind[84].

In a steady state global axisymmetric MHD model, Alfvén waves were incorporated self-consistently into a two-dimensional simulation of the solar corona and solar wind in the region from $1\,R_{\rm s}$ (solar radius) to $5\,\rm AU$[113]. Assuming that Alfvén waves provide the additional heating and acceleration of the solar wind, the model can quantitatively reproduce the observed bimodal structure and morphology of both slow and fast solar wind streams. Some other numerical MHD simulation models[114−115] were also presented to study the acceleration of the solar wind by Alfvén waves.

Hollweg[86] argued that Alfvén waves were preferred for the solar wind heating because they are dominant at 1 AU and are associated with high-speed solar wind streams, and nonlinear damping of large-amplitude Alfvén waves can significantly contribute to the heating of the solar wind[39]. Through non-resonant wave-particle scattering, Alfvén waves can efficiently heat protons, randomizing the proton motion in the direction perpendicular to the background magnetic field[116−118].

Furthermore, a test particle simulation of stochastic heating and acceleration of minor ions by obliquely propagating low-frequency Alfvén waves showed that the ions can gain a bulk parallel velocity equal to the Alfvén speed, when the wave amplitude exceeds the threshold value for stochasticity[119]. Such a heating mechanism may be important for the mass-proportional minor ion temperatures and the differential speed (roughly equal to the local Alfvén speed) between minor ions and protons observed by Ulysses in the solar wind[120−121]. The result is consistent with previous observations of pronounced differential speeds and temperatures between hydrogen and helium ions, which is closely related to strong Alfvén wave activity in fast solar wind streams[122]. In the slow solar wind, the pronounced proton temperature anisotropy and ion differential speed were also found to occur simultaneously with intense Alfvén wave activity[123], which may not always be enough to generate the observed high-speed solar wind although the waves were considered to be necessary to the observations of simultaneously high speeds and temperatures of recurrent streams originating in coronal holes (see the review by Hollweg[124]). Similarly, Bavassano *et al.*[6] made an extrapolation that in regions near the Sun hourly-scale Alfvénic fluctuations should not play an important role in solar wind heating and acceleration.

In another word, the evidence that Alfvén waves are the fundamental cause of the solar wind heating and acceleration is far from definitive, and thus further observational, theoretical, and numerical simulation efforts should be made to resolve the issue.

4 Relation to Discontinuities

Directional Discontinuities (DDs)[125], sharp angular changes in interplanetary magnetic fields, are one of the fundamental microstructures in solar wind, including both Rotational Discontinuities (RDs) and TDs[126−127], the spectrum of which contains about half of the power of the full solar wind magnetic field over the inertial subrange[128]. RDs and TDs are qualitatively different[129]. RDs have a field component normal to the discontinuity plane and propagate in the plasma frame, but TDs do not. Changes in the magnetic field and velocity across an RD are correlated as for Alfvén waves, while the field magnitude and density are nearly constant. So we usually say that RDs are Alfvénic. TDs separate distinct plasmas, and can have significant changes in field magnitude and density across them.

DDs may be plasma boundaries (flux tube walls), current sheets produced by MHD turbulence, fractures in large-scale velocity shears, current sheets formed by global magnetic relaxation, or steepening of Alfvén waves[130], and so it is difficult to classify DDs observed in the solar wind. Some researchers[131−134] (and references therein) suggested that in the solar wind most DDs are identified as RDs, but others[15−16,25,35,56,135−138] argued that most of the DDs appear to be TDs. Tsurutani *et al.*[139] surmised that the phase steepened edges of Alfvén waves are some form of intermediate shocks, which can have properties of both RDs and TDs[140]. Therefore, determining the properties of discontinuities in the solar wind is necessary for a full understanding of the nature of the solar wind fluctuations[130].

An intimate relationship was found between Alfvén waves and discontinuities[133]. More discontinuities are found in the Alfvén wave intervals than other intervals[21]. The large discontinuity concentration shows that the dominant population is associated with Alfvénic fluctuations which are ubiquitous in the solar wind[25]. Towards the trailing edge of a CIR, it is also difficult to distinguish waves from discontinuities[19]. We will address pertinent questions concerning the relationship between Alfvén waves and DDs in detail in the following sections.

4.1 Rotational Discontinuities

Belcher and Davis[4] called the sharply crested Alfvén wave an RD, which can better explain the observed properties in a straightforward manner only assuming that all waves should propagate away from the Sun. In this case, RDs are often an integral part of Alfvén waves.

Most DDs in Alfvénic intervals were shown to be rotational rather than tangential[131−133]. Nearly all the observed RDs were propagating outward from the Sun, which indicates that inward (or sunward) propagating Alfvénic fluctuations seldom steepen into RDs before reaching 1 AU[132]. The arc-polarized phase-steepened Alfvén waves (Alfvén wave plus discontinuity)[133], are present in about 30%~60% of the time in the high-latitude Ulysses data[36]. Another study[21] of Ulysses data in the ecliptic plane indicated that most events can be best fitted by an arc-polarized Alfvén wave model with imbedded RDs propagating along the minimum variance direction, based on the comparison of the observations with features expected from different models.

Numerical simulations of large amplitude arc-polarized Alfvén waves have been performed. Such nonlinear Alfvén waves are shown to be both dispersive and compressive and to generate imbedded RDs[141−147] when the nonlinear wave magnetic pressure force causes the larger amplitude portion of the wave to quickly occupy the region with smaller amplitude portion[25]. This mechanism tends to be in support of nearly field aligned normals of RDs.

It was proposed that RDs and Alfvén waves may be generated as a result of magnetic reconnections[148], and the waves were suggested to accelerate particles there[149]. Similar results were obtained by numerical simulations of magnetic reconnection generating RDs imbedded in Alfvén waves in the outflow region[150−151].

The RD option is preferred by the enhanced frequency of discontinuities within Alfvén wave trains in the fast polar solar wind[133], and discontinuities with large normal field components should be common. But the main problem is the lack of an acceptable explanation for DDs with small normal field components, independent of the type of solar wind flows. Although the triangulation results show that no clearly identified RDs exist in the Cluster data set[152], Lin *et al.*[153] found that several interplanetary DDs with small normal field components could be RDs due to well-correlated velocity and magnetic field fluctuations, and conducted 1D hybrid simulations to show that these RDs are stable. They also pointed out that these RDs are likely generated by magnetic reconnections near the Sun, and the small normal field components are possibly caused by the interaction of these RDs with fast shocks, which provides an alternative generation mechanism of these interplanetary RDs.

Besides, RDs, as an integral part of Alfvén waves, have a subunity Walén slope to be discussed in Section 4.2. Further work needs to be undertaken in this area.

4.2 Subunity Walén Slope for Alfvén Waves and RDs

The Walén relation (1) can be applied to any point for small- and large-amplitude Alfvén waves and in the whole transition region of an RD[24,37]. The Walén slope, defined as $R_{\rm VB} = \sqrt{\mu_0\rho}v_i/AB_i$ where the subscript i denotes the coordinate component (*e.g.*, x, y or z in Cartesian coordinates), may be a distinguishing feature[154] and an indicator for the degree of the Alfvénicity of the solar wind fluctuations. Alfvén waves are usually identified if the correlation coefficients between v_i and B_i are larger than 0.6 for two or three components[15]. Obviously, from the Walén relation (1), $R_{\rm VB}$ is expected to equal unity for an ideal Alfvén wave or RD in the solar wind and is arbitrary for a TD. One of the unresolved puzzles in space plasma physics is why $R_{\rm VB}$ is consistently less than unity for both Alfvén waves[4,63,155] and discontinuities in the solar wind[127,156].

For Alfvén waves, Goldstein *et al.*[155] suggested that pickup ions might contribute to the anisotropy required to raise $R_{\rm VB}$ to unity, but Neugebauer[154] thought that seems unlikely. In addition, some studies suggested that $R_{\rm VB} < 1$ may be caused by inward propagating Alfvén waves superimposed on the general outward propagating wave population, which effect may be important for the general wave field in the solar wind and but should be negligible for surface waves on an interplanetary TD[154]. But the Helios data showed that the decrease in the Alfvénic correlation may sometimes be caused by the presence of compressive fluctuations rather than a superposition of Alfvén waves with mixed propagation directions[157]. Besides, multifluid effects, inferred from the analysis of Helios 2 observations of highly Alfvénic fluctuations, can explain only in part the subunity Walén slope[158].

For RDs, Neugebauer *et al.*[127] took into account anisotropies, electrons and alpha particles, but could not raise the average value of $R_{\rm VB}$ above 0.77, and Puhl-Quinn and Scudder[159] concluded that the misassignment of minor ion species as protons surely contributes to subunity Walén slopes of RDs, but is probably not the main cause.

For both Alfvén waves and RDs, Wu and Lee[160] examined the Hall effect on the ion and electron Walén slopes in Hall-MHD with an isotropic pressure, but the effect can be ignored in the solar wind because the characteristic spatial scale of this effect is much smaller than the wavelength of Alfvén waves therein. Electron flow velocities[161] and the acceleration of an RD[162−163] are also considered to improve the Walén tests of Alfvén waves or RDs, and the results are still not satisfactory.

All in all, why $R_{\rm VB}$ of Alfvén waves and RDs is less than unity has different causes, including hidden sources of anisotropy, particle species except protons, the presence of waves, some nonlinear effects, observational inaccuracies (systematic errors in measurement), and noise, *etc.* Future studies should figure out the relative contribution of these causes to the subunity Walén slope for Alfvén waves and RDs.

4.3 Tangential Discontinuities

The possibility that the interplanetary medium is dominated by TDs is very important for the solar wind structure, because TDs separate distinct plasma regions without plasma flow and would considerably reduce the energetic particle diffusion[152].

Individual TDs (or current sheets) in the solar wind are reported to be Alfvénic[15−16,25,56,135−138], and are much more Alfvénic than the fluctuations between these discontinuities[164]. So Neugebauer[154] pointed out that the high $\boldsymbol{v}$-$\boldsymbol{B}$ correlation is not a useful parameter for distinguishing RDs from TDs because such a high correlation could also be present for surface Alfvén waves traveling along a TD[15]. These TDs may be the convected structures or 2D turbulence depicted by Tu and Marsch[27] and Bieber *et al.*[165], and may make a significant contribution to magnetic field power[103].

The Alfvénicity of the TDs remains an open question, although various theoretical interpretations for the question have been put forward[16,72,105]. Recently, Borovsky[130] interpreted this Alfvénicity as flux tubes undergoing Alfvénic motion due to the braiding of the flux tubes, large-scale shears and compressions, magnetic reconnections, *etc.* The decay of a spectrum of low frequency Alfvén waves[28,58,166−167] may not be a viable mechanism for the Alfvénic motions of flux tubes[130]. Moreover, we still do not know exactly the driver of these fluctuations within the flux tubes of the solar wind plasma.

Another possibility is that most TDs, at least in the fast wind, are a particular case of RDs, *i.e.*, phase-steepened large-amplitude Alfvén waves[133] propagating very slowly when the wave vector is nearly perpendicular to the ambient magnetic field[79,138,168−170]. This interpretation is completely different from those mentioned above. The correlated velocity and magnetic field fluctuations do not have a readily available explanation if most of these discontinuities are TDs associated with flux tubes[25]. Further work is required to confirm and understand the apparent Alfvénic nature of TDs in the solar wind.

4.4 Abundances of RDs and TDs

Previous single spacecraft studies using MVA[171] suggest that most discontinuities are rotational. For example, the high-latitude Ulysses observations of DDs show that 61% of them are RDs, but only 5% are TDs[36]. However, normals estimated from inter-spacecraft timings between three spacecraft showed that very few were unambiguous RDs, with 77% likely to be tangential and $< 20\%$ of the magnetic field at the discontinuity threading the normal plane[103]. It should be, however, pointed out that different criteria have been used to classify discontinuities in previous studies mentioned in this section, and that different methods *e.g.*, MVA and the triangulation method[152], may also yield different abundances of

RDs and TDs (see Section 4.5 for details).

Clearly the relative occurrence of RDs and TDs is very different from what we used to know. A detailed comment on the abundances of RDs and TDs was made by Neugebauer[154], who cannot decide between RD and TD options. The answer to this question requires further efforts in modeling and careful analysis of new observations.

4.5 Methods for Discontinuity Normal Estimation

To estimate discontinuity normals, MVA[171] is often used in most previous studies[172] (and references therein). The minimum variance direction of the magnetic fluctuations is associated with the timescale of interest. In fast polar solar wind region, the minimum variance direction for the daily variations of the magnetic field components is more radial than along the magnetic field with increasing solar distance[71], which cannot be well explained by Alfvén theory.

Errors in the normal vector obtained from MVA can be large particularly when the intermediate to minimum eigenvalue ratio is small[172]. It has been suggested that results from the MVA technique are likely affected by both waves and noise superimposed on the discontinuity structure. For example, it was proposed[103−105] that MVA often detects surface Alfvén waves[72] on TDs.

Another method to determine the discontinuity normal is the triangulation method, assuming that the discontinuity surface is planar and has constant propagation velocity between different spacecraft, which is likely not a serious problem for closely spaced spacecraft. However, Neugebauer[154] pointed out that neither MVA nor the triangulation method is perfect for determining the discontinuity normal.

In addition, three methods were applied by Knetter *et al.*[152] to find the discontinuity normals, based on a detailed statistical analysis of interplanetary discontinuities in the solar wind. The cross-product normals agree fairly well with the triangulation normals, which are mostly in a direction nearly perpendicular to the magnetic field. But the accuracy of MVA is strongly affected by both the eigenvalue ratio of MVA and the angle between the magnetic field vectors on either side of the discontinuity, so Knetter *et al.*[152] concluded that the cross-product method likely yields more reliable normal estimates than MVA for discontinuities with small normal magnetic field components, consistent with the results of Horbury *et al.*[173]. There is still no clear answer as to which method is best for the discontinuity normal estimation.

5 Relation to Other Structures

5.1 Flux Tubes and Ropes, MCs, and ICMEs

Solar wind fluctuations can be viewed as a superposition of Alfvén waves and convective structures[27,51]. The observed flux tubes[174] could be pictured as convective structures imbedded in the fast solar wind streams, and they might form a spaghetti-like substructure[175−177] probably originating in the solar atmosphere. The Alfvénic motion of flux tubes[130] may explain the Alfvénicity of TDs (see Section 4.3). On the other hand, the dominance of outwardly propagating Alfvénic fluctuations with large spatial scales ($> 0.1\,\mathrm{AU}$)[92], similar to those observed by Helios 1 and 2[65], may be twisted flux tubes in the solar wind[19]. There is a strong relation between Alfvén waves and flux tubes, which is important for studies of the solar wind structures.

It is possible that sometimes Alfvén wave trains might have magnetic field structures similar to flux ropes[178], and some previously reported small flux ropes were classified as Alfvén wave trains[64]. These waves may be generated in small-scale solar activities[179−180] and carried outward to the interplanetary space in the form of flux ropes. Another wave generation mechanism in the solar wind is the local magnetic reconnection, which can also generate small-scale flux ropes[178,181]. Then one question arises: what is the relationship between Alfvén waves and flux ropes in the solar wind.

Signatures of Alfvén waves were also found in Magnetic Clouds (MCs)[182−183] and in magnetic cloud boundary layers with possible DDs and magnetic reconnections therein[184], which reveals the interaction of the magnetic cloud with the solar wind.

Few Interplanetary Coronal Mass Ejections (ICMEs) observed in situ could have typical signatures of Alfvén waves, including time sections possibly related to the occurrence of hot proton beams[182] and to a prominence[183] that suggests a possible solar origin for Alfvén waves. But the waves are indicated to be rarely seen inside ICMEs[185], so it is possible for the waves in an expanding ICME to die out with increasing heliocentric distance via some dynamic processes[183].

Recently, Gosling *et al.*[42] showed that an extremely rare solar event observed by both the ACE and Wind spacecraft can be interpreted as a torsional Alfvén wave[186−187] embedded within a small magnetic flux rope erupting from the Sun. The torsional wave was likely produced by the distortions of these preexisting flux ropes[188−189] and was probably a portion of a larger ordinary ICME-related disturbance. But Gosling *et al.*[42] pointed out that many flux ropes in the solar wind may originate primarily from three-dimensional reconnection inside the legs of coronal mass ejections from the Sun[190−191] rather than from ejection of a preexisting flux rope. These results indicate the possibility that Alfvén waves are closely related to flux ropes and ICMEs, which is important for understanding the nature of the dynamics of those structures.

5.2 Magnetic Decreases

Magnetic Decreases (MDs) or Magnetic Holes (MHs) are decreases in the magnetic field magnitude, and are often detected in interplanetary space[134,192−194]. The total pressure is constant across these structures, to first order[193]. These MDs/MHs have been shown to be collocated with the discontinuities or phase steepened edges of Alfvén waves[7,195].

Related wave-particle interactions in MDs/MHs can heat the plasma and dissipate the energy of the phase-steepened Alfvén waves[195], and the ponderomotive force associated with such Alfvén waves can contribute to the perpendicular particle energization[139,195−196], which in the steepening region diminishes the magnitude of the magnetic field through the diamagnetic effects[25]. If the process is true, the magnetic decreases are not parts of the discontinuities or Alfvén waves themselves, and can be viewed as byproducts of the Alfvén wave dissipation process[140].

From a kinetic viewpoint, a one-dimensional hybrid simulation[197] was performed and showed that large-amplitude Alfvén waves in CIRs can be transformed into MDs between the CIR Reverse Shock (RS) and Stream Interface (SI) by the Alfvén wave-RS interaction, similar to the previous results from one-dimensional MHD simulations[198]. This model is supported by the noticeable appearance of MDs between the SI and RS[199] as a possible mechanism for MD formation, and these MDs are expected to reduce the CIR dimension and lower the efficiency of particle acceleration at CIR shocks[197].

MDs can also be generated by localized inhomogeneities introduced by large-amplitude Alfvén waves[200] and by a pair of oppositely propagating Alfvén waves[79]. We would anticipate that Alfvén waves would be crucial to the MD formation in the solar wind.

Another point should be mentioned: the interaction of energetic particles with the MD portions of the nonlinear Alfvén waves leads not only to pitch angle scattering but also to cross-field diffusion[201], so wave-particle interaction theories should consider those effects of both nonlinear waves and their compressive feature.

6 Summary and Open Questions

This review examines an eclectic selection of publications concerning observations and the theory of large-amplitude Alfvén waves in the solar wind, which include the observational properties of the waves, wave heating and acceleration of the solar wind, the relation of the waves to DDs, MDs/MHs, and to other relatively large-scale structures such as flux tubes/ropes, MCs, and ICMEs in interplanetary space. Since the interpretation of these observations is usually troublesome and unsatisfactory, we presented only the observational facts and related theoretical models without an attempt to draw definite conclusions at the present time. We wish to highlight recent progress in observational studies of Alfvén waves in the solar wind and to formulate a microscopic picture of the nature of Alfvénic fluctuations.

Although much progress has been made in observations, theoretical interpretations, and numerical simulations of Alfvén waves in the solar wind, many fundamental aspects remain unresolved. As mentioned in previous sections, these important questions are summarized as follows.

(1) Could Alfvénic fluctuations be viewed as a superposition of noninteracting Alfvén waves or the consequence of turbulence in which energy cascades from large scales to small scales[81]? Without wave-wave interactions, why can large-amplitude Alfvén waves still have a Kolmogorov's power law expected for isotropic turbulence[23]?

(2) The problem of why the Walén slope is generally smaller than unity for both Alfvén waves and RDs must await more extensive investigations.

(3) What are the origin and generation mechanisms of Alfvén waves and related discontinuities in the solar wind? How do they evolve with increasing heliocentric distance in interplanetary space?

(4) How do large-amplitude Alfvén waves interact with microscale structures like discontinuities (*i.e.*, RDs and TDs) and MDs/MHs in the solar wind? What is the relationship between Alfvén waves and these structures?

(5) Surface Alfvén waves on TDs are relevant to the cause of the Alfvénic motions of flux tubes in the solar wind[130], but there is still no direct observations of such waves. Do they really exist?

(6) Why some particular discontinuities (*i.e.*, flux tube walls) are so Alfvénic[130]? Might DDs with both small magnitude changes and small normal components be TDs or RDs with small normal components and small magnitude changes[154]?

These questions, arising from the observations reviewed in this paper, are of fundamental importance to large-amplitude Alfvén wave studies.

Our work is still underway to develop new methods for improving the subunity Walén slope of Alfvén waves, and for determining the wave normal direction and the background magnetic field more precisely than those used in most previous studies. And in order to settle these above mentioned questions, we need high time resolution plasma and magnetic field measurements, multipoint observations from spacecraft to distinguish spatial structures from temporal variations, nonlinear theories to analyze the large-amplitude Alfvén waves, more complete theories on the evolution of the waves, long temporal runs to identify the nonlinear Alfvén wave dissipation process[140] and to study how the waves and DDs evolve over longer distances and periods of time, and better error analyses to determine the wave vector or the discontinuity normal direction.

Some key issues listed above may have been investigated in the past, but the answers to them generally remain unclear or ambiguous at this stage. It is clear that there is still a long way to go before a full understanding of the physical nature of Alfvén waves and their role in heating and accelerating the solar wind.

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