

# Evidence of Kinetic Alfvén Waves in the Solar Wind at 1 AU

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Received: 23 October 2012 / Accepted: 13 February 2013 / Published online: 8 March 2013  
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**Abstract** Several independent lines of observational evidence of the existence of kinetic Alfvén waves (KAWs) in the solar wind are briefly reviewed. Each piece of evidence is inconclusive when considered separately, but when taken together, it is reasonable to conclude from these observations that KAWs in the form of kinetic Alfvén turbulence are almost always present in the free-flowing solar wind near 1 AU and, by inference, perhaps throughout much of the heliosphere.

**Keywords** Fluctuations · Kinetic Alfvén waves · Solar wind · Turbulence

## 1. Introduction

Waves and fluctuations in the solar wind span a wide range of scales, from magneto-hydrodynamic (MHD) scales to kinetic scales, and contain valuable information about the kinetic processes that operate in the interplanetary medium. In the past 50 years, a large number of studies of the waves and fluctuations at MHD scales have been conducted, facilitated by the availability of well-resolved in-situ plasma and magnetic field data at MHD scales. However, relatively few studies have been performed on the waves and fluctuations at kinetic scales  $\rho_i^{-1} < k < \rho_e^{-1}$  since plasma measurements with sufficiently high time resolution are almost non-existent, electric field measurements from 1 Hz to 100 Hz are in many respects inadequate, and practically the only data available to study these small-scale fluctuations are high time resolution magnetic field data (the proton gyro-radius  $\rho_i$  and other symbols are defined at the end of the Introduction). As a consequence, observational knowledge of kinetic-scale fluctuations in the solar wind is remarkably limited after 50 years of research.

To date, observations have shown that electromagnetic ion-cyclotron waves (EMIC waves) propagating within a few tens of degrees of the direction parallel to the interplanetary magnetic field with spacecraft-frame frequencies on the order of 1/2 Hz and wavenumbers

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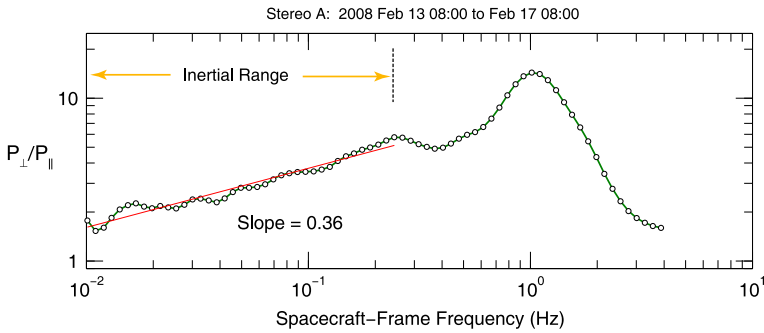
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of order  $kc/\omega_{pi} \sim 1$ , where  $c/\omega_{pi}$  is the proton inertial length, are common in the free solar wind near 1 AU (Behannon, 1976; Tsurutani *et al.*, 1994; Jian *et al.*, 2009, 2010; He *et al.*, 2011; Podesta and Gary, 2011b, 2011a; Podesta, 2012a). The Doppler-shifted proton cyclotron frequency is approximately 1 Hz at 1 AU. In a stable plasma with  $\beta_i \sim 1/2$ , nearly parallel-propagating EMIC waves are usually strongly damped at wavenumbers near  $kc/\omega_{pi} = 1$  (Gary, 1986, 1999; Harmon, 1989), and, therefore, EMIC waves observed near  $kc/\omega_{pi} = 1$  are most likely generated by local plasma instabilities in the solar wind as indicated by Leubner and Viñas (1986) and references therein.

When  $\beta_p$  is on the order of unity, the EMIC wave has the interesting property that as the angle of propagation increases continuously from zero (parallel propagation) to within a few tens of degrees of the direction perpendicular to the ambient magnetic field, the sense of polarization of the mode changes from left- to right-handed (Gary, 1986; Hollweg, 1999). That is, at quasi-perpendicular propagation the projection of the electric field vector onto the plane perpendicular to  $\mathbf{B}_0$  rotates in the same sense as the electron-cyclotron motion. At kinetic scales where  $k_{\perp}\rho_i$  is not negligible compared to unity and  $k_{\perp} \gg k_{\parallel}$ , this right-hand polarized mode is called the kinetic Alfvén wave, abbreviated hereafter as KAW (Hollweg, 1999; Howes *et al.*, 2006).

While nearly parallel-propagating EMIC waves have been the central focus of theoretical studies of wave-particle interactions and plasma processes in the solar wind and solar corona for many decades (Marsch, 1999; Isenberg, 2001; Hollweg and Isenberg, 2002), serious interest in KAWs in solar wind physics is relatively new. The KAW has risen in importance in solar-wind and coronal physics over the past decade in part because of a resurgence of interest documented in publications of Leamon *et al.* (1998a, 1999a), Hollweg (1999), Shukla *et al.* (1999), Cranmer and van Ballegooijen (2003), Voitenko and Goossens (2004), and Bale *et al.* (2005), for example, and in part because of new ideas in the theory of kinetic plasma turbulence motivated by Goldreich and Sridhar's *anisotropic* theory of incompressible MHD turbulence (Goldreich and Sridhar, 1995, 1997) that were later developed by Quataert (1998), Quataert and Gruzinov (1999), Howes *et al.* (2006), Schekochihin, Cowley, and Dorland (2007) and others (Terry, McKay, and Fernandez, 2001; Terry and Smith, 2007, 2008; Howes *et al.*, 2008a, 2008b, 2011; Schekochihin *et al.*, 2008, 2009; Smith and Terry, 2011). These theoretical advances have established a new paradigm for anisotropic turbulence in collisionless magnetized plasmas in which KAWs and kinetic Alfvén fluctuations play a central role.

*Why Should KAWs Exist in the Solar Wind at 1 AU?* Since the pioneering work by Coleman (1967, 1968), a popular school of thought has held that solar wind turbulence drives an energy cascade from large to small scales. Assuming that solar-wind turbulence is supported predominantly by Alfvén waves or Alfvénic fluctuations at MHD scales, as observations suggest, and that on average the energy cascade in wave-vector space transfers energy in the direction perpendicular to the ambient magnetic field, as MHD simulations indicate (Shebalin, Matthaeus, and Montgomery, 1983; Oughton, Priest, and Matthaeus, 1994; Matthaeus *et al.*, 1996; Cho and Vishniac, 2000), then as the energy cascade proceeds to higher wavenumbers, the turbulence becomes progressively more anisotropic such that the energy spectrum is concentrated in regions where  $k_{\perp} \gg k_{\parallel}$ . The observed anisotropy of solar wind turbulence at MHD scales exhibits a wavenumber dependence consistent with theoretical predictions (Horbury, Forman, and Oughton, 2008; Podesta, 2009, 2010; Luo and Wu, 2010; Wicks *et al.*, 2010; Forman, Wicks, and Horbury, 2011) as seen, for example, in Figure 1. Consequently, when the energy cascade reaches kinetic scales, the turbulent fluctuations with  $k_{\perp} \gg k_{\parallel}$  will naturally change from Alfvén waves or Alfvénic fluctuations



**Figure 1** Solar wind measurements of the ratio of the power spectrum  $P_{\perp}$  measured along the direction perpendicular to the local mean magnetic field to the spectrum  $P_{\parallel}$  measured along the direction parallel to the local mean magnetic field. The linear least-squares fit in log-log coordinates over the range from  $10^{-2}$  Hz to  $2.5 \times 10^{-1}$  Hz (red line) has a slope of 0.36, which is consistent with the predictions of Goldreich and Sridhar’s anisotropic theory of incompressible MHD turbulence. The data used in the analysis were acquired in a long-lived high-speed stream near 1 AU. Similar results are shown in Figure 8 of Podesta (2009).

to KAWs or kinetic Alfvén fluctuations. For this reason, solar wind fluctuations at kinetic scales are expected to include KAWs in the form of strong kinetic Alfvén turbulence (Howes *et al.*, 2006, 2008a, 2008b, 2011; Schekochihin, Cowley, and Dorland, 2007; Schekochihin *et al.*, 2008, 2009; Boldyrev and Perez, 2012).

The purpose of this paper is to review the observational evidence for the existence of KAWs in the solar wind. Even though evidence of quasi-parallel-propagating EMIC waves or quasi-parallel-propagating magnetosonic/whistler waves may be obtained directly from visual inspection of magnetic field waveforms and hodograms, for example, evidence for the existence of KAWs in the solar wind is relatively indirect and requires data analysis techniques that are more intensive and more sophisticated. Only recently has a convincing body of evidence for KAWs in the solar wind been obtained. This evidence is summarized point by point in Sections 2–7.

### 1.1. Definitions and Terminology

The ambient direct-current (DC) magnetic field and the local mean magnetic field are denoted by  $\mathbf{B}_0$ , the solar wind magnetic field is denoted  $\mathbf{B}$  or  $\mathbf{B}(t)$ . The importance of using the local mean magnetic field to describe fluctuations in turbulent magnetized plasmas was demonstrated by Cho and Vishniac (2000) and Maron and Goldreich (2001); its definition in applications to solar-wind measurements is summarized by Podesta (2012a). The terms “parallel” and “perpendicular” refer to the directions parallel and perpendicular to the local mean magnetic field unless specifically noted otherwise. A plane wave with wave vector  $\mathbf{k}$ , frequency  $\omega \geq 0$ , and phase  $\phi = \mathbf{k} \cdot \mathbf{x} - \omega t$  is called “quasi-parallel” when  $|k_{\parallel}| \gg k_{\perp}$  and “quasi-perpendicular” when  $k_{\perp} \gg |k_{\parallel}|$ , where  $k_{\perp} = \sqrt{k_x^2 + k_y^2}$  is the magnitude of the perpendicular component of  $\mathbf{k}$  and  $k_{\parallel} = \mathbf{k} \cdot \mathbf{B}_0/B_0$  is the parallel component of  $\mathbf{k}$ . Taylor’s hypothesis relates the frequency in the spacecraft frame to the wave vector by  $\omega_{sc} \simeq \mathbf{k} \cdot \mathbf{V}_{sw}$ , where  $\mathbf{V}_{sw}$  is the solar wind velocity.

Most of the plasma physics notation used in this paper is standard:  $k = |\mathbf{k}| = 2\pi/\lambda$  is the wavenumber,  $\omega = 2\pi\nu$  is the frequency in radians per second,  $\nu = \omega/2\pi$  is the frequency in Hz,  $\rho_i = v_{i,\perp}/\omega_{ci}$  is the thermal proton gyro-radius,  $\rho_e = v_{e,\perp}/\omega_{ce}$  is the thermal electron gyro-radius,  $c/\omega_{pi}$  is the proton inertial length,  $c/\omega_{pe}$  is the electron inertial

length,  $\omega_{ci} = eB/m_i$  is the proton cyclotron frequency,  $\omega_{ce} = eB/m_e$  is the electron cyclotron frequency,  $\omega_{pi} = \sqrt{n_i e^2 / \epsilon_0 m_i}$  is the proton plasma frequency,  $\omega_{pe} = \sqrt{n_e e^2 / \epsilon_0 m_e}$  is the electron plasma frequency,  $n_s$  and  $T_s$  are the number density and kinetic temperature of particle species  $s$  ( $s = i, e, \alpha$ ),  $v_{th,s} = \sqrt{2\kappa T_s / m_s}$  is the thermal speed of particle species  $s$ , and  $v_{s,\perp} = \sqrt{2\kappa T_{s,\perp} / m_s}$ . In the solar wind the lower-hybrid frequency is approximately  $\omega_{LH} \simeq \sqrt{\omega_{ci} \omega_{ce}}$ . The physical constants include the speed of light  $c$ , the elementary charge  $e > 0$ , Boltzmann's constant  $\kappa$ , the vacuum permittivity  $\epsilon_0$ , and the vacuum permeability  $\mu_0$  (SI units). The ratio of the thermal pressure of the protons to the magnetic pressure is  $\beta_i = n_i \kappa T_i / (B^2 / 2\mu_0)$  and, similarly, for the electrons  $\beta_e = n_e \kappa T_e / (B^2 / 2\mu_0)$ . Near 1 AU, the solar wind is characterized by the typical values  $\beta_i \sim 1/2$  and  $\beta_e \sim 1/2$ . The relation “ $x \sim y$ ” means that  $x$  is of the same order of magnitude as  $y$ .

In the Vlasov–Maxwell wave theory, EMIC and KAW are abbreviations for “electromagnetic ion-cyclotron” and “kinetic Alfvén wave,” respectively. For wave propagation quasi-parallel to the local mean magnetic field, the “Alfvén/ion-cyclotron wave” and the “EMIC wave” are the same thing; at quasi-perpendicular propagation, this mode changes into the KAW. The “magnetosonic/whistler wave” is the low-frequency extension of the whistler wave for  $\omega < \omega_{ci}$  (Gary, 1993). At quasi-perpendicular propagation and for frequencies in the range  $\omega_{LH} < \omega < \omega_{ce}$ , the whistler wave is often called the lower hybrid wave, which is approximately electrostatic (Marsch and Chang, 1983; Rosenberg and Gekelman, 2001; Verdon *et al.*, 2009a, 2009b).

In Fourier space, the perpendicular energy spectrum  $E(k_{\perp})$  is related to the full three-dimensional energy spectrum  $E_{3D}(\mathbf{k})$  by

$$E(k_{\perp}) = \int_{-\infty}^{\infty} dk_{\parallel} \int_0^{2\pi} d\phi k_{\perp} E_{3D}(\mathbf{k}), \quad (1)$$

where  $\phi$  is the azimuthal angle defined by  $k_x = k_{\perp} \cos \phi$  and  $k_y = k_{\perp} \sin \phi$ , and the  $k_z$ -axis is aligned with  $\mathbf{B}_0$ . Therefore, the total energy is

$$E = \int_0^{\infty} E(k_{\perp}) dk_{\perp}. \quad (2)$$

The perpendicular spectrum or  $k_{\perp}$ -spectrum has a Kolmogorov scaling when  $E(k_{\perp}) \propto k_{\perp}^{-5/3}$ .

## 2. Enhanced Density Fluctuations When $k\rho_i \sim 1$

Leamon *et al.* (1998a, 1999a) were the first to suggest that the so-called 2D component of solar wind fluctuations in the dissipation range consists primarily of KAWs; the 2D component is defined as those solar wind fluctuations with wave-vectors nearly perpendicular to the ambient magnetic field. Furthermore, Leamon *et al.* (1998a, 1999a) developed the idea that Landau-damping of KAWs is responsible for the dissipation of solar wind turbulence which, at that time, was believed to occur in the neighborhood of the spectral break that marks the transition from MHD to kinetic scales; see Figures 10 and 11 in Leamon *et al.* (1999a).

Soon after the first publications by Leamon *et al.* (1999a), Hollweg (1999) reviewed the properties of KAWs derived using a two-fluid approach. Two of the characteristic features of the KAW that Hollweg discusses are (1) an increase in the relative density fluctuations at wavenumbers near the proton inertial length  $kc/\omega_{pi} = 1$  and (2) an increase in the magnetic compressibility at wavenumbers near the proton gyro-radius scale  $k_{\perp}\rho_i = 1$  (in the solar wind near 1 AU,  $\rho_i \sim c/\omega_{pi}$  and these two length-scales are close to each other on a log-log

plot). As defined in this section, the magnetic compressibility is the ratio of the power of the parallel component of the magnetic field fluctuations to the power in the two perpendicular components (Harmon, 1989).

Following an earlier suggestion by Harmon (1989) that the increasing density fluctuations of the KAW as a function of wavenumber should produce an observable flattening of the spectrum of density fluctuations in the solar wind, Hollweg (1999) pointed out that the enhanced proton density fluctuations near the proton gyro-radius scale observed by Neugebauer (1975, 1976) may be caused by KAWs in the solar wind; see also Neugebauer, Wu, and Huba (1978). The data analyzed by Neugebauer are exceptionally high time resolution plasma data rarely obtained in the solar wind. Hollweg (1999) also commented that the increase in the magnetic compressibility observed in the dissipation range by Leamon *et al.* (1998a) is consistent with the existence of KAWs in the solar wind. This point is discussed in more detail in Section 7.

Neugebauer's observations of enhanced proton density fluctuations appear as a small bump or flattening of the power spectrum near the proton gyro-radius scale, as first predicted by Harmon (1989). A similar flattening is sometimes observed in spacecraft measurements of electron density fluctuations (Celnikier *et al.*, 1983; Celnikier, Muschietti, and Goldman, 1987; Harvey, Celnikier, and Hubert, 1988; Kellogg and Horbury, 2005) which, by similar reasoning, have been interpreted by Chandran *et al.* (2009) as evidence of KAWs in the free solar wind.

### 3. Wave Dispersion at Kinetic Scales

Bale *et al.* (2005) used measurements of electric and magnetic field spectra to show how the wavenumber dependence of the phase speed and wave dispersion at the transition to kinetic scales near  $k\rho_i \sim 1$  are more consistent with KAWs than with magnetosonic/whistler waves. A further investigation along these lines was carried out by Salem *et al.* (2012), who showed that the wavenumber dependence of the electric-to-magnetic field ratio  $\delta E_y/\delta B_z$  in GSE coordinates and the ratio of the r.m.s. amplitude of the parallel magnetic field component to the total fluctuating magnetic field  $\delta B_{\parallel}/\delta B$  agree better with the theoretical predictions for KAWs than with those for magnetosonic/whistler waves.

Sahraoui *et al.* (2010) analyzed multi-spacecraft *Cluster* observations using the  $k$ -filtering technique – also known as the wave-telescope technique – to obtain the first measurements of the wave vectors  $\mathbf{k}$  of solar wind fluctuations at kinetic scales as well as the frequency versus wavenumber relation in the plasma frame. Although these measurements were restricted to  $k_{\perp}\rho_i < 2$ , the measured wave vectors near  $k_{\perp}\rho_i = 1$  were all within a few degrees of the direction perpendicular to the local mean magnetic field and the measured  $\omega$  versus  $k$  relation agreed better with the theoretical dispersion relation for KAWs than with that of magnetosonic/whistler waves. A similar wave-telescope analysis by Narita *et al.* (2011) affirmed the quasi-perpendicular nature of the fluctuations near  $k\rho_i = 1$ , but the  $\omega$  versus  $k$  analysis showed no clear agreement with any one dispersion relation. It did, however, suggest that the quasi-perpendicular fluctuations with wavenumbers near  $k\rho_i = 1$  may be characterized by a wide range of frequencies in the plasma frame that extend above and below the proton cyclotron frequency, indicating the possible presence of modes other than KAWs. The higher frequency waves may have been missed in the analysis by Sahraoui *et al.* (2010) because of spatial aliasing effects, and further analysis is needed to clarify the results obtained by these two groups.

Sahraoui *et al.* (2010) also reported steep wavenumber spectra  $\sim k_{\perp}^{-5}$  in the limited range  $1 < k_{\perp}c/\omega_{pi} < 2$ , as shown in Figure 6 of Sahraoui *et al.* (2010). These spectra may represent a transition to the shallower  $\sim k_{\perp}^{-2.7}$  spectra expected to occur at higher wavenumbers than those shown in Figure 6 of Sahraoui *et al.* (2010), which are discussed in the next section. The steep wavenumber spectra in this transition region may be a consequence of proton heating via turbulent dissipation at these scales and, if so, the spectra may contain important information about proton heating processes that have yet to be explained. On the other hand, the steep wavenumber spectra may indicate a breakdown of Taylor's hypothesis at these scales. Measurements of wavenumber spectra using the wave-telescope technique are limited by spatial aliasing to wavelengths greater than twice the spacecraft separation and, unfortunately, for the multi-spacecraft data presently available the measurable wavenumber spectra are limited to wavenumbers such that  $k_{\perp}\rho_i \lesssim 2$ ; see Section 3.1.2 in Narita (2012) and references therein.

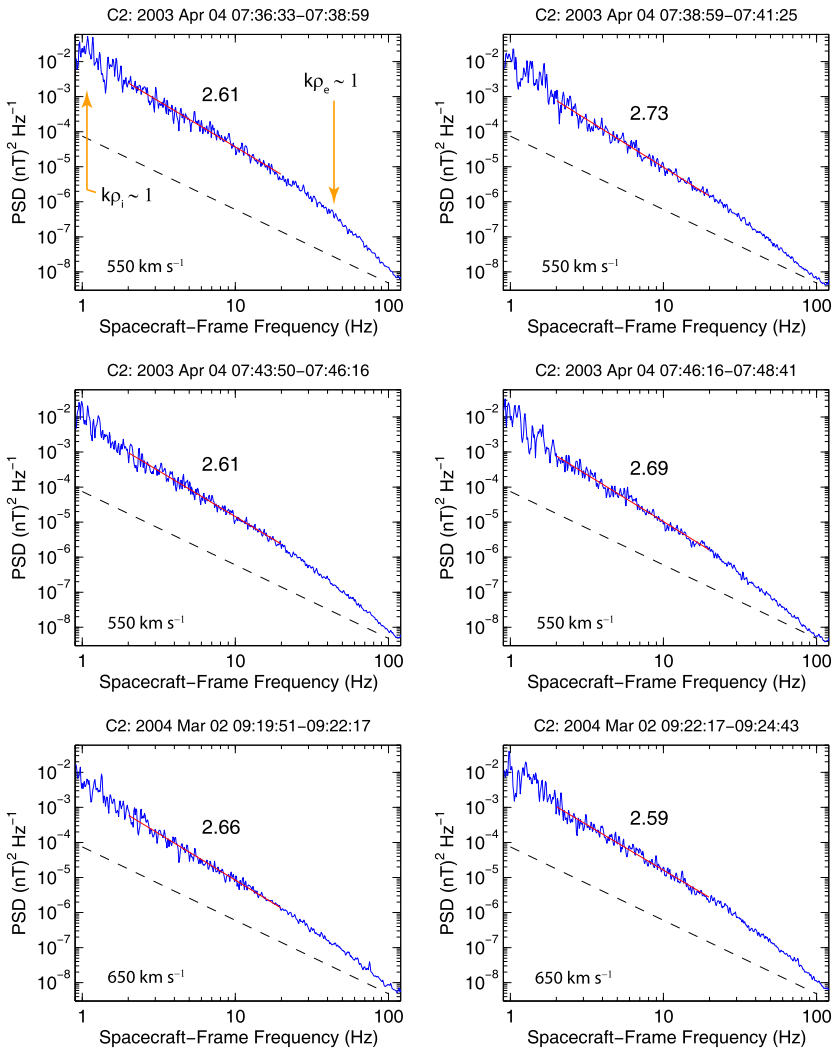
With one possible exception, the above-mentioned wave measurements support the hypothesis that KAWs rather than magnetosonic/whistlers form the energetically dominant component of solar wind fluctuations at  $k_{\perp}\rho_i \sim 1$ . However, observations of quasi-parallel propagating fluctuations with wavenumbers localized near  $k_{\parallel}c/\omega_{pi} \sim 1$  exhibit power levels that are sometimes comparable to the oblique or nearly perpendicular propagating fluctuations, that is, over the limited wavenumber range where both families of fluctuations co-exist (He *et al.*, 2011; Podesta and Gary, 2011a; Podesta, 2012a). In these observations, the perpendicular-propagating fluctuations have been tentatively identified as KAWs and the nearly parallel-propagating fluctuations have been tentatively identified as either ion-cyclotron waves or magnetosonic/whistler waves; the quasi-parallel waves are likely generated locally by plasma instabilities (Podesta and Gary, 2011b). Thus, while KAWs are usually energetically dominant, there exist other fluctuations at these scales with energies comparable to KAWs.

#### 4. Spectral Indices of B and $n_e$ at Kinetic Scales

Recent numerical simulations have shown that kinetic Alfvén turbulence in collisionless high beta plasmas,  $\beta_i \sim \beta_e \sim 1$ , is characterized by a perpendicular<sup>1</sup> magnetic energy spectrum proportional to  $k_{\perp}^{-\alpha}$  in the approximate range  $\rho_i^{-1} < k_{\perp} < \rho_e^{-1}$  with a spectral index  $\alpha \approx 2.7$  (Howes *et al.*, 2008b, 2011; Boldyrev and Perez, 2012). And because kinetic Alfvén turbulence is characterized by an equipartition of energy between electron density fluctuations and magnetic field fluctuations (Terry, McKay, and Fernandez, 2001; Terry and Smith, 2007, 2008; Schekochihin *et al.*, 2009; Boldyrev and Perez, 2012), the electron density spectrum naturally has the same spectral index as the magnetic field spectrum (Boldyrev and Perez, 2012).

In comparison with simulations, solar wind observations in the frequency range from  $\sim 3$  Hz to  $\sim 30$  Hz in the spacecraft-frame show that both the magnetic field and electron density spectra have spectral indices close to 2.7 (Sahraoui *et al.*, 2009, 2010, 2011; Kiyani *et al.*, 2009; Alexandrova *et al.*, 2009, 2010; Chen *et al.*, 2010, 2012; Sahraoui and Goldstein, 2011; Podesta, 2011, 2013). Samples of the magnetic field spectra are shown in Figure 2. Because Taylor's hypothesis is usually valid for KAWs such that  $k_{\perp} \gg k_{\parallel}$  and  $k_{\perp}\rho_i < \rho_i/\rho_e \sim \sqrt{m_i/m_e}$ , KAW fluctuations are approximately "frozen into the flow" and

<sup>1</sup>The perpendicular spectrum is defined at the end of the Introduction.



**Figure 2** Examples of the power spectral density (PSD) of magnetic field fluctuations (trace spectra) in the solar wind at 1 AU obtained using 450 Hz data from the search-coil magnetometer on board *Cluster* spacecraft number 2 (C2) acquired when the spacecraft was not magnetically connected to the Earth's bowshock. Each spectrum is computed using a DPSS data taper with  $NW = 4$  (Percival and Walden, 1993) and smoothed at logarithmically spaced frequencies using a smoothing window with a frequency-dependent bandwidth  $\Delta\nu$  such that  $\Delta\nu/\nu = 2\%$ . The spectral index is the slope of the line in log–log space (red line) obtained from a linear least-squares fit to the smoothed data over the frequency band from 2 Hz to 20 Hz. The noise floor of the search-coil measurements (for a single orthogonal component of  $\mathbf{B}$ ) is indicated by the dashed line (Cornilleau-Wehrlin *et al.*, 2003). Based on Taylor's hypothesis and the measured plasma parameters, the wavenumbers where  $k\rho_i \sim 1$  and  $k\rho_e \sim 1$  occur at 1 Hz and 43 Hz, respectively, and are the same in all six plots.

the measured solar wind spectra may be interpreted as reduced wavenumber spectra within the approximate range  $\rho_i^{-1} < k_{\perp} < \rho_e^{-1}$ . Taylor's hypothesis is valid as long as the phase speed of the waves is much slower than the solar wind speed; its range of application in the

solar wind can be estimated using the approximate dispersion relation for KAWs (Howes *et al.*, 2006)

$$\omega \simeq \frac{|k_{\parallel} v_A| (k_{\perp} \rho_i)}{\sqrt{\beta_i + 2/(1 + T_e/T_i)}}. \tag{3}$$

It follows that the spectra of  $\mathbf{B}$  and  $n_e$  observed in the solar wind at kinetic scales are consistent with the wavenumber spectra of kinetic Alfvén turbulence.

Simulations of three-dimensional electron MHD (EMHD) turbulence are characterized by a perpendicular magnetic energy spectrum that scales approximately like  $k_{\perp}^{-7/3}$  (Biskamp *et al.*, 1999; Cho and Lazarian, 2004, 2009), a result that does not agree with the typical  $k_{\perp}^{-2.7}$  behavior seen in solar wind observations. However, the EMHD equations do not take into account the perpendicular velocity perturbations of the ions required to maintain charge neutrality at low frequencies and do not properly account for the coupling between parallel magnetic field fluctuations and electron density fluctuations that is important when  $\beta_i \sim 1$  (Schekochihin *et al.*, 2009). The appropriate generalization of EMHD to include these effects leads to the theory called electron-reduced MHD (ERMHD) by Schekochihin *et al.* (2009), which is essentially identical to the system of equations derived by Boldyrev and Perez (2012) and by others in the past. Simulations of plasma turbulence based on these equations (Boldyrev and Perez, 2012) show that the perpendicular magnetic energy spectrum and the electron density spectrum scale approximately like  $k_{\perp}^{-8/3}$ , which closely agrees with solar wind observations at kinetic scales.

The ERMHD equations are similar in many respects to a two-fluid approach, which is advantageous for direct numerical simulations, but they do not take collisionless damping processes into account and cannot shed light on the effects of Landau- and transit-time damping on the spectral scaling. Nevertheless, the results may still be relevant for the solar wind.

For kinetic Alfvén turbulence, the scaling of the spectrum of electric field fluctuations is  $k_{\perp}^2$  times that of the magnetic field spectrum. To see this, note that the perpendicular electron velocity is  $\mathbf{v}_{\perp} = \mathbf{E} \times \mathbf{B}_0/B_0^2$ , so that  $\mathbf{E}_{\perp} = -\mathbf{v}_{\perp} \times \mathbf{B}_0$  and, therefore,  $\mathbf{E}_{\perp}$  and  $\mathbf{v}_{\perp}$  scale alike, which we denote by  $E_{\perp} \sim v_{\perp}$  (this definition of ‘ $\sim$ ’ applies in this paragraph only). From Faraday’s law,

$$\omega B_{\parallel} = \mathbf{B}_0 \cdot (\mathbf{k} \times \mathbf{E})/B_0 = \mathbf{k} \cdot (\mathbf{E} \times \mathbf{B}_0)/B_0 = B_0 \mathbf{k}_{\perp} \cdot \mathbf{v}_{\perp} \sim k_{\perp} v_{\perp}, \tag{4}$$

and, using  $\omega \propto k_{\parallel} k_{\perp}$ , this implies  $k_{\parallel} B_{\parallel} \sim v_{\perp}$ . But  $\mathbf{k} \cdot \mathbf{B} = 0$  implies  $k_{\parallel} B_{\parallel} \sim k_{\perp} B_{\perp}$  and, therefore,

$$k_{\perp} B_{\perp} \sim v_{\perp} \sim E_{\perp}. \tag{5}$$

For KAWs,  $E_{\perp}^2 \gg E_{\parallel}^2$  and the stated result follows. Therefore, a magnetic field spectrum  $k_{\perp}^{-7/3}$  corresponds to an electric field spectrum  $k_{\perp}^{-1/3}$  and a magnetic field spectrum  $k_{\perp}^{-8/3}$  corresponds to an electric field spectrum  $k_{\perp}^{-2/3}$ . Electric field measurements performed using *Cluster* data by Bale *et al.* (2005) and Kellogg *et al.* (2006) show a flattening of the spectrum at the transition to kinetic scales, but the measurements are dominated by noise at high frequencies (Stuart Bale, personal communication, 2012; Paul Kellogg, personal communication, 2012) and measurements of the spectral slope in that range are unreliable; for example, in the range  $2.5 \leq k\rho_i < 10$  in Figure 3 of Bale *et al.* (2005). The electric field spectrum of solar wind fluctuations at 1 AU has probably never been accurately measured between 1 Hz and 100 Hz in the spacecraft frame (Kellogg, 2008; Forrest Mozer, private communication, 2012) and, therefore, it remains to compare solar wind electric field spectra



to theoretical predictions and numerical simulations of kinetic Alfvén turbulence. This is an important goal for future space missions.

Since the 1970s, in-situ measurements of electric and magnetic fields at spacecraft-frame frequencies from a few Hz to a few hundred Hz have been interpreted as magnetosonic/whistler waves because whistlers were initially thought to be the only electromagnetic modes possible in the frequency range  $\omega_{ci} < \omega < \omega_{ce}$  (Neubauer, Musmann, and Dehmel, 1977; Gurnett, 1991) and because the observed phase speeds were consistent with whistler waves (Beinroth and Neubauer, 1981; Lengyel-Frey *et al.*, 1996; Zhang, Matsumoto, and Kojima, 1998; Lin *et al.*, 1998, 2003). Apparently, the possible existence of quasi-perpendicular KAWs was not considered in connection with wave observations in the 1970s or 1980s with the notable exception of the unrelated work by Harmon (1989). The relative energies and wave-vector distributions of magnetosonic/whistler turbulence versus kinetic Alfvén turbulence in the kinetic regime are important issues that require further investigation from both theoretical and observational points of view. Relevant studies at MHD scales have recently been performed by Howes *et al.* (2012) and Klein *et al.* (2012); studies at both MHD and kinetic scales have been performed by TenBarge *et al.* (2012).

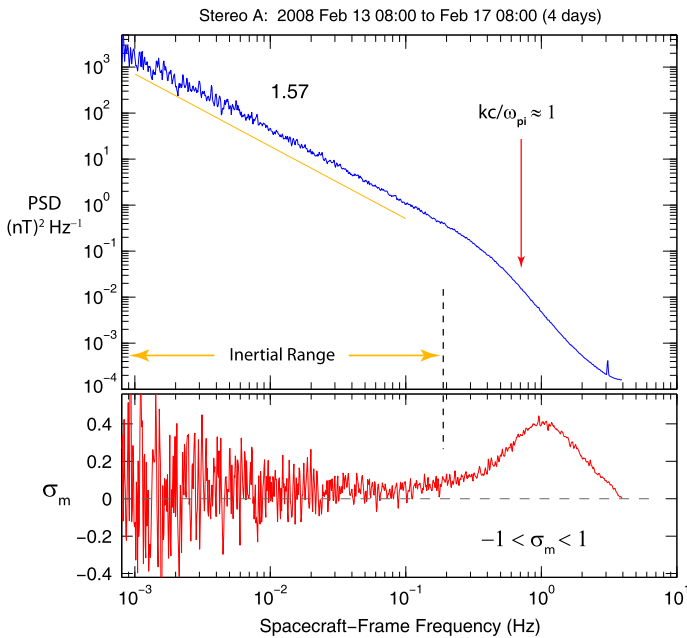
## 5. Magnetic Helicity Spectrum at Kinetic Scales

Throughout the inertial range at 1 AU the normalized magnetic helicity spectrum  $\sigma_m$  is zero, on average, while at kinetic scales  $\sigma_m$  shows a distinctive peak near  $kc/\omega_{pi} = 1$  that may be explained by waves with a predominantly right-hand sense of polarization propagating away from the Sun (Goldstein, Roberts, and Fitch, 1994; Leamon *et al.*, 1998a). A sample spectrum is shown in Figure 3. Following an idea by Denskat, Beinroth, and Neubauer (1983),<sup>2</sup> it was suggested by Goldstein, Roberts, and Fitch (1994) that this peak may be caused by ion-cyclotron damping of a cascade of predominantly outward-propagating quasi-parallel Alfvén/ion-cyclotron waves near the spectral break. This would have the consequence that only right-hand polarized quasi-parallel magnetosonic/whistler waves cascade through the spectral break to higher wavenumbers, an idea developed further by Leamon *et al.* (1998b, 1999b), Li, Gary, and Stawicki (2001), Stawicki, Gary, and Li (2001), and others.

An alternative interpretation proposed by Howes and Quataert (2010) is that the observed peak in the magnetic helicity spectrum  $\sigma_m$  may be caused by KAWs which, like magnetosonic-whistler waves, are right-hand polarized. Howes and Quataert (2010) showed that an anisotropic spectrum of predominantly outward-propagating KAWs with  $k_{\perp} \gg k_{\parallel}$  would produce a reduced  $\sigma_m$  spectrum in reasonable agreement with observations (Howes and Quataert, 2010) and, therefore, a turbulent spectrum of KAWs can explain the observed spectral peak in  $\sigma_m$ . Moreover, Howes and Quataert (2010) pointed out that because theory and simulations indicated that the energy cascade in MHD turbulence is directed primarily perpendicular to the ambient magnetic field, it was most likely that the fluctuations at dissipation range scales would consist of a cascade of quasi-perpendicular KAWs. In the view of Howes and Quataert, any power in quasi-parallel fluctuations would be relatively small compared to the quasi-perpendicular fluctuations and, consequently, the ion-cyclotron damping scenario seemed unlikely.

The parallel cascade postulated in the ion-cyclotron damping scenario has been seen in one dimensional kinetic simulations by Yoon and Fang (2008, 2009) and two-dimensional

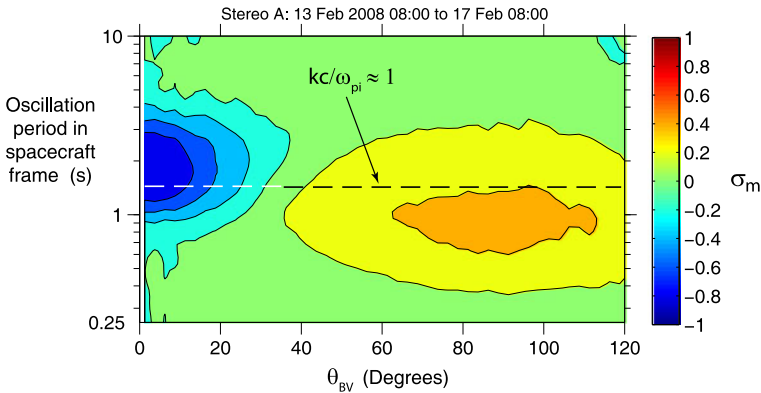
<sup>2</sup>See the left-hand side of p. 65 of Denskat, Beinroth, and Neubauer (1983).



**Figure 3** Sample of the solar wind magnetic field spectrum (trace spectrum) and the normalized magnetic helicity spectrum  $\sigma_m$  obtained using 1 AU data from the STEREO-A spacecraft for an unusually long-lived high-speed stream for which  $V \simeq 655 \text{ km s}^{-1}$ ,  $n_p \simeq 2.2 \text{ cm}^{-3}$ ,  $T_p \simeq 1.6 \times 10^5 \text{ K}$ , and  $\beta_p \simeq 0.7$ . The spectral slope in the inertial range as measured over the interval from  $10^{-3} \text{ Hz}$  to  $10^{-1} \text{ Hz}$  is 1.57; the best-fit line in log-log space is offset for easier viewing. Using Taylor's hypothesis, the approximate wavenumber where  $kc/\omega_{pi} = 1$  occurs at 0.7 Hz is indicated by the vertical arrow. A peak in the magnetic helicity spectrum is clearly seen immediately after the spectral break.

kinetic simulations by Verscharen *et al.* (2012). Simulations such as these may eventually provide a physical basis for the ion-cyclotron damping scenario in which the damping of the parallel EMIC cascade causes perpendicular heating of the protons – a potentially relevant, if not dominant process in the solar wind. Thus, it is possible that both the KAW scenario and the ion-cyclotron damping scenario play a role in the solar wind. However, observations of parallel-propagating fluctuations near  $kc/\omega_{pi} = 1$  suggest they are likely caused by plasma instabilities in the solar wind (Podesta and Gary, 2011b) and, in cases where that is true, ion-cyclotron waves grow rather than damp and the ion-cyclotron damping scenario cannot explain the observed magnetic helicity spectrum. More detailed kinetic simulations are needed to verify and investigate the nature of parallel energy cascades in three-dimensional collisionless plasma turbulence and their relationship, if any, to the perpendicular cascades almost always seen in simulations. Coupling between parallel electron heating and perpendicular proton heating via lower-hybrid waves may also be important (Marsch and Chang, 1983; Laming, 2005; Verdon *et al.*, 2009a, 2009b) and observations should be used to study this process.

Recently, the reduced magnetic helicity spectrum  $\sigma_m$  has been analyzed as a function of the angle  $\theta_{BV}$  between the direction of the local mean magnetic field and the local flow velocity of the solar wind (He *et al.*, 2011; Podesta and Gary, 2011a; Podesta, 2012a). This enables the spectrum  $\sigma_m$  to be measured at different look angles with respect to the local mean magnetic field, which allows one to investigate  $\sigma_m$ , roughly speaking, as a function



**Figure 4** The reduced magnetic helicity spectrum  $\sigma_m$ , in color, is measured at a series of equally spaced angles  $\theta_{BV}$  and then superposed to obtain this composite image. Each vertical slice gives the spectrum  $\sigma_m$  at a particular look angle  $\theta_{BV}$  relative to the direction of the local mean magnetic field. Using Taylor's hypothesis, the vertical axis may equivalently be expressed in terms of downward-increasing wavenumber; the dashed line indicates the wavenumber where, using Taylor's hypothesis,  $kc/\omega_{pi} \approx 1$ . The angle bins are of size  $\Delta\theta = 2.5^\circ$ . Data are from the STEREO-A spacecraft for a long-lived high-speed stream during the four-day interval from 13 to 17 February 2008.

of the direction of the wave propagation. A sample of the results is shown in Figure 4. The data indicate two distinct populations of electromagnetic fluctuations near  $k_{\perp}\rho_i = 1$ : A population of fluctuations with left-hand polarization (in the spacecraft frame) observed when looking nearly parallel to  $\mathbf{B}_0$ , the blue spot near  $\theta_{BV} = 0$  in Figure 4, and a family with predominantly right-hand polarization (in the spacecraft frame) observed when looking at oblique and quasi-perpendicular angles relative to  $\mathbf{B}_0$ , the orange and yellow spot centered on  $\theta_{BV} = 90^\circ$  in Figure 4. The quasi-parallel fluctuations have tentatively been identified as EMIC waves propagating away from the Sun or magnetosonic/whistler waves propagating toward the Sun along the interplanetary magnetic field, while the quasi-perpendicular waves have tentatively been identified as KAWs.

To help interpret these observations, a model of the three-dimensional spectrum of magnetic field fluctuations in the solar wind, a model of the three-dimensional spectrum of magnetic field fluctuations in the solar wind, was constructed by He *et al.* (2012a), consisting of a superposition of a quasi-parallel spectrum of EMIC waves and a quasi-perpendicular spectrum of kinetic Alfvén waves with overall amplitudes chosen to be consistent with the parallel and perpendicular spectra measured in the solar wind. The waves in the model propagate predominantly outward (away from the Sun) for wavelengths  $\lambda > \rho_i$  and are balanced (equal powers of outward and inward propagating waves at a given  $\mathbf{k}$ ) for  $\lambda < \rho_i$ , with a smooth transition between the two at  $\lambda = \rho_i$ . A balanced spectrum at kinetic scales was found to be necessary to produce the high wavenumber cutoff seen in the observations of  $\sigma_m(k, \theta_{BV})$  as anticipated by Howes and Quataert (2010), however, the cutoff seen in published observations is close to the Nyquist frequency (He *et al.*, 2011; Podesta and Gary, 2011a; Podesta, 2012a) and higher frequency observations suggest this cutoff sometimes occurs at much higher frequencies (unpublished *Cluster* observations). The good agreement between the theoretical model and solar wind observations shown in Figure 3 of He *et al.* (2012a) indicates that the quasi-perpendicular signal in Figure 4 above may be produced by a spectrum of KAWs in the solar wind, as proposed by Howes and Quataert (2010). In an independent study, Klein, Howes, and TenBarge (manuscript in preparation) have used the technique of

Klein *et al.* (2012) to simulate what a spacecraft would measure when it is flown through a spectrum of predominantly outward propagating randomly phased KAWs. This showed that the orange and yellow spot in Figure 4 may be reproduced remarkably well in this manner. Hence, kinetic Alfvén turbulence in the solar wind can satisfactorily explain the orange and yellow spot seen in observations such as those shown in Figure 4.

Wave measurements have not yet identified the modes responsible for the observed signal at quasi-parallel propagation in Figure 4, which may be caused by either EMIC waves propagating away from the Sun, magnetosonic/whistlers propagating toward the Sun, or both. Podesta and Gary (2011b) have shown that because of the differential streaming of alpha particles relative to protons, the proton temperature anisotropy instability generates EMIC waves that propagate predominantly away from the Sun when  $T_{\perp p} > T_{\parallel p}$ , and magnetosonic/whistler waves propagating toward the Sun when  $T_{\perp p} < T_{\parallel p}$ . Moreover, the range of unstable wavenumbers near  $kc/\omega_{pi} = 1$  coincides approximately with the region of strong quasi-parallel wave activity in Figure 4. Thus, these instabilities provide a natural explanation of the data. Measurements of the two electric field components perpendicular to the heliocentric radial direction together with simultaneous magnetic field measurements are needed to clearly identify the waves; simultaneous high-resolution measurements of particle distribution functions would be needed to confirm the instability mechanism.

He *et al.* (2012b) have investigated hodograms of the fluctuations that cause the orange spot in Figure 4. They found that the fluctuations were right-hand polarized, as the magnetic helicity measurements indicate, and attempted to use the orientation of the polarization ellipse to identify whether the fluctuations are KAWs or quasi-perpendicular magnetosonic/whistler waves. However, theoretical calculations of the polarization ellipse for the magnetosonic/whistler were based on the ion-Bernstein branch of the dispersion relation as pointed out by TenBarge *et al.* (2012) and, therefore, the relation  $\delta B_{\parallel} > \delta B_{\perp}$  for the magnetosonic/whistler shown in Figure 4 of He *et al.* (2012b) actually belongs to the ion-Bernstein mode. Consequently, analyses of the polarization ellipse by He *et al.* (2012b) do not rule out the quasi-perpendicular magnetosonic/whistler as claimed, they only show that the observations are consistent with the polarization properties of KAWs. The nomenclature of the various wave modes in the hot plasma dispersion relation when  $k_{\perp} \gg k_{\parallel}$  can be confusing because a single continuous curve or branch of the dispersion relation for a particular angle of propagation may be associated with different types of waves in different ranges of wavenumbers and because the appearance of ion Bernstein modes can break up the otherwise continuous curves for a particular mode such as the magnetosonic/whistler wave (Verdon *et al.*, 2009b; Podesta, 2012b). A review of the nomenclature and properties of the different modes arising from the Vlasov–Maxwell dispersion relation when  $k_{\perp} \gg k_{\parallel}$  and  $\omega < \omega_{LH}$  would make a useful contribution to the solar wind literature.

## 6. Variance Anisotropy as a Function of $\beta$

The identification of specific kinds of waves using spacecraft data is often facilitated by means of various dimensionless ratios that characterize the different modes (Gary and Winske, 1992; Gary, 1993; Denton *et al.*, 1995; Schwartz, Burgess, and Moses, 1996; Gary and Smith, 2009; Salem *et al.*, 2012; Howes *et al.*, 2012). One such ratio is the variance anisotropy  $(\delta B_{\perp})^2/(\delta B_{\parallel})^2$  or its reciprocal  $(\delta B_{\parallel})^2/(\delta B_{\perp})^2$ , where  $\delta B_{\perp}$  and  $\delta B_{\parallel}$  are the r.m.s. amplitudes at a given wavenumber (Belcher and Davis, 1971; Harmon, 1989; Leamon *et al.*, 1998a; Smith, Vasquez, and Hamilton, 2006; Hamilton *et al.*, 2008;

TenBarge *et al.*, 2012; Podesta and TenBarge, 2012). A closely related quantity analyzed by Gary and Smith (2009) is

$$C_{\parallel} = \frac{(\delta B_{\parallel})^2}{(\delta B)^2}, \quad (6)$$

where  $(\delta B)^2 = (\delta B_{\perp})^2 + (\delta B_{\parallel})^2$ , a quantity they call the magnetic compressibility – nomenclature that is common in the magnetospheric literature. It is readily shown that

$$\frac{(\delta B_{\parallel})^2}{(\delta B_{\perp})^2} = \frac{C_{\parallel}}{1 - C_{\parallel}}, \quad (7)$$

and, consequently, as  $C_{\parallel}$  increases from 0 to 1, the reciprocal variance anisotropy increases from 0 to  $+\infty$  with

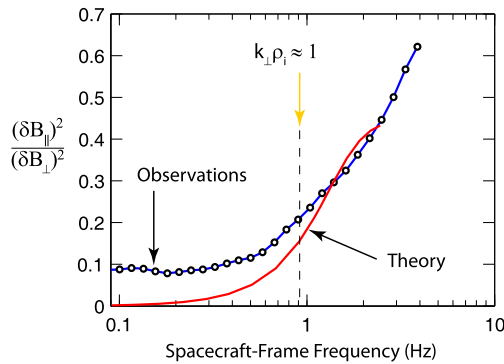
$$0 \leq C_{\parallel} \leq 1 \quad \text{and} \quad 0 \leq \frac{(\delta B_{\parallel})^2}{(\delta B_{\perp})^2} \leq \infty. \quad (8)$$

Gary and Smith (2009) showed, among other things, that the magnetic compressibility  $C_{\parallel}$  has a  $\beta$  dependence for KAWs that is distinctly different from that of quasi-perpendicular magnetosonic/whistler waves. The authors showed that for a fixed wave-vector  $k_{\perp} \gg k_{\parallel}$  and  $k_{\perp}\rho_i \sim 1$ , the quantity  $C_{\parallel}$  is an increasing function of  $\beta$  for KAWs and a nearly constant function of  $\beta$  for quasi-perpendicular whistlers, where  $\beta = \beta_i + \beta_e$  and, in their study,  $\beta_i = \beta_e$ . By comparison, solar wind measurements of the variance anisotropy versus  $\beta_i$  shown in Figure 8 of Hamilton *et al.* (2008) indicate that, on average,  $C_{\parallel}$  is an increasing function of  $\beta_i$  at dissipation range scales. Thus, it is fair to conclude that the average trend seen in solar wind data is consistent with the behavior of KAWs and inconsistent with that of quasi-perpendicular magnetosonic/whistler waves. However, a mixture of both types of waves cannot be ruled out and, therefore, the conclusions drawn by Gary and Smith (2009) were not conclusive one way or the other. In general, it is of interest to compare theoretical predictions directly with solar wind observations by plotting them both on the same graph so that quantitative comparisons may be made. Unfortunately, Gary and Smith (2009) did not do so and, consequently, direct quantitative comparisons between theory and observations were not part of their analysis. This should be investigated in the future.

## 7. Wavenumber Dependence of the Variance Anisotropy Near $k\rho_i \sim 1$

The KAW has the property  $(\delta B_{\parallel})^2/(\delta B_{\perp})^2 \rightarrow 0$  in the small wavenumber MHD limit  $k_{\perp}\rho_i \ll 1$ , consistent with the property of the MHD Alfvén wave  $\delta B_{\parallel} = 0$ . When  $\beta_i \sim 1$ , the inequality  $(\delta B_{\parallel}/\delta B_{\perp})^2 \ll 1$  holds as the wavenumber  $k_{\perp}\rho_i$  gradually increases from zero until, when  $k_{\perp}\rho_i$  is no longer negligible compared to unity, the ratio  $(\delta B_{\parallel}/\delta B_{\perp})^2$  quickly increases to values on the order of 1/2, as can be seen from the theory curve in Figure 5, see also Hollweg (1999, Figure 4) and Podesta and TenBarge (2012, Figure 2).

The significant increase in the ratio  $(\delta B_{\parallel}/\delta B_{\perp})^2$  that occurs near  $k_{\perp}\rho_i = 1$  when  $\beta_i \sim 1$  is a characteristic feature of the KAW that can be compared against observational data. Podesta and TenBarge (2012) measured the ratio  $(\delta B_{\parallel}/\delta B_{\perp})^2$  using relatively homogeneous solar wind data in high-speed streams and compared the measurements to theoretical predictions of the ratio  $(\delta B_{\parallel}/\delta B_{\perp})^2$  for an axisymmetric spectrum of randomly phased KAWs (plane waves) obtained from the Vlasov–Maxwell hot plasma dispersion relation. Qualitatively and quantitatively, reasonably good agreement between theory and observations was found in each of the 20 different high-speed streams that were studied. A sample of their results



**Figure 5** The reciprocal variance anisotropy  $(\delta B_{\parallel})^2/(\delta B_{\perp})^2$  as a function of the perpendicular wavenumber  $k_{\perp}\rho_i$  observed in a high-speed stream (black dots) is compared to the theoretical prediction for a spectrum of KAWs (red curve). The frequency in the spacecraft frame that corresponds to the normalized wavenumber  $k_{\perp}\rho_i \approx 1$  is indicated by the dashed line. The smooth increase in the data when  $k_{\perp}\rho_i \sim 1$  agrees well with the theoretical predictions. The data are from the STEREO-A spacecraft for the time interval 27 July 2011 12:00 to 30 July 18:00, 3.25 days, when  $V \approx 621 \text{ km s}^{-1}$  and  $\beta_i \sim 0.7$ ; this is one of the intervals analyzed by Podesta and TenBarge (2012).

is shown in Figure 5. It is especially noteworthy that i) the wavenumber where the ratio  $(\delta B_{\parallel}/\delta B_{\perp})^2$  starts to increase and ii) the amplitude of the increase from  $k_{\perp}\rho_i \simeq 1$  to  $k_{\perp}\rho_i \simeq 2$  are both in close agreement with the theory. The plateau in the ratio  $(\delta B_{\parallel}/\delta B_{\perp})^2 \sim 0.1$  seen in Figure 5 at low wavenumbers  $k_{\perp}\rho_i \ll 1$  is caused by compressible fluctuations in the inertial range that cannot be removed from the data; however, this plateau is irrelevant for the investigation of KAWs in the range  $k_{\perp}\rho_i \sim 1$ . Thus, it is reasonable to conclude that the observed wavenumber dependence of the ratio  $(\delta B_{\parallel}/\delta B_{\perp})^2$  near  $k_{\perp}\rho_i = 1$  supports the existence of a spectrum of KAWs in the solar wind at 1 AU.

## 8. Conclusions

The combined research efforts of various groups over the past few years have produced a significant body of evidence that suggests kinetic Alfvén turbulence consisting of KAWs or kinetic Alfvén fluctuations is ubiquitous in the solar wind at 1 AU and perhaps throughout the heliosphere. An important goal of solar wind science is to obtain complete knowledge of the types of waves and fluctuations that populate the solar wind, the physical properties of these waves, and their relationship to the kinetic processes that shape and regulate particle distribution functions in the solar wind. The progress reported here is a small step in that direction. Whether there exist observational signatures of KAWs in three-dimensional ion and electron distribution functions in the solar wind is an important question that needs to be addressed.

We emphasize that the observational evidence reviewed here applies primarily to wavenumbers near the proton gyro-radius scale  $k\rho_i \sim 1$ , except for the scaling of the spectra of  $\mathbf{B}$  and  $n_e$  at kinetic scales  $k\rho_i \gg 1$ , which by itself is inconclusive. Much work remains to be done to provide convincing observational evidence of the nature, composition, and wave-vector distributions of the fluctuations at scales  $\rho_i^{-1} < k < \rho_e^{-1}$  as well as the fluctuations at scales  $\omega_{ci} < \omega < \omega_{ce}$ . At the present time, the true nature of solar wind fluctuations at these scales, including electron scales, is highly controversial from a theoretical point of

view. More complete observational data, including electric field data, and a more extensive analysis of existing data are needed to resolve this important issue.

The existence of strong kinetic Alfvén turbulence in the solar wind and solar corona has important consequences for space science and astrophysics that have just begun to be explored. The stochastic heating of charged particles known to occur in a large-amplitude wave (Chen, Lin, and White, 2001; Johnson and Cheng, 2001; White, Chen, and Lin, 2002; Voitenko and Goossens, 2004) may also occur in a turbulent wavefield. This nonlinear process may be responsible for perpendicular heating of protons and heavy ions in the solar wind and solar corona through interactions with low-frequency KAW turbulence at wavelengths near the ion gyro-radius scale  $k_{\perp} \rho_i \sim 1$ , where the wave frequencies are much lower than the ion-cyclotron frequency  $\omega \ll \omega_{ci}$  (White, Chen, and Lin, 2002; Chandran, 2010; Chandran *et al.*, 2010). Kinetic Alfvén turbulence also has significant effects on interstellar scintillation (Smith and Terry, 2011) with implications for interplanetary scintillation that have yet to be investigated.

**Acknowledgements** The contents of this paper are based on an invited talk presented at the Solar Wind Thirteen conference held on the Big Island of Hawaii in June of 2012. This review, which covers many details not included in the talk, was motivated a few months after the meeting by personal comments from an esteemed solar wind scientist and plasma physicist whose incredulous view on the existence of KAWs in the solar wind is confuted by experimental data. I am grateful to several of my colleagues who provided valuable feedback that significantly improved this paper. This research was supported by the NASA Solar and Heliospheric Physics Program and by the NSF Shine Program.

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