Ion Kinetic Scale in the Solar Wind Observed

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This Letter shows the first results from the solar wind monitor onboard the Spektr-R spacecraft which measures plasma moments with a time resolution of 31 ms. This high-time resolution allows us to make direct observations of solar wind turbulence below ion kinetic length scales. We present examples of the frequency spectra of the density, velocity, and thermal velocity. Our study reveals that although these parameters exhibit the same behavior at the magnetohydrodynamic scale, their spectra are remarkably different at the kinetic scale.

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Introduction.—The solar wind provides a unique example to characterize the nature of turbulent plasmas through *in situ* spacecraft observations. Solar wind turbulence has been studied for many decades [1–3] because understanding its properties is important to determine the universal features of turbulence and to estimate collisionless plasma heating in general [4,5].

The observations of the solar wind velocity, density, and magnetic field consist of a time series of broadband disordered fluctuations usually characterized by power-law frequency spectra over all measured scales. The presence of a strong interplanetary magnetic field (IMF) results in low-frequency fluctuations that are usually described within a magnetohydrodynamic (MHD) approach. At these scales (below $\approx$ tenths of Hz at 1 AU), the one-dimensional turbulent energy spectrum of magnetic fluctuations in the spacecraft frame follows a power-law behavior with a slope of $-5/3$ [6], suggestive of a Kolmogorov-like inertial range [7,8] and consistent with a turbulent cascade.

Podesta, Roberts and Goldstein [9] discuss the difference between the value of the power-law exponents for magnetic field (close to $-5/3$) and velocity (closer to $-3/2$) fluctuations (e.g., Refs. [10–13]) and concluded that this difference is not consistent with any of the current theories of Alfvénic turbulence and is one of the currently unsolved problems in turbulence theory. Salem *et al.* [12] attribute this inconsistency either to a strong anisotropy in the solar wind fluctuations or to the influence of solar wind compressibility.

The characteristics of turbulence in the dissipation range (at higher frequencies) are not well understood; the turbulent magnetic field spectrum follows a steeper power law with a spectral index varying from -2 to -4 (e.g., Refs. [8,14–17]).

The steepening of the spectrum at higher frequencies has been attributed to ion cyclotron damping of Alfvén waves [18–20], Landau damping of kinetic Alfvén waves [14,17,21,22], or scattering of oblique whistler waves [23,24]. Based on measured advanced composition explorer spacecraft magnetic field spectra and plasma parameters, Markovskii *et al.* [25] found that the spectral steepening is a nonlinear process that could come from linear cyclotron damping and from wave dispersion associated with the Hall effect.

To estimate the power-law exponent for plasma fluctuations in the dissipation range, the authors use the measurements of the electric field [22,26,27] or the spacecraft potential [e.g., Ref. [28]] as a proxy for the solar wind velocity or electron density for frequencies within ion or even electron kinetic scales.

Various explanations have been proposed for the location of the break in the magnetic field spectrum, for example, that it coincides with the ion (proton) cyclotron frequency [7,19,20,29] or that the fluctuation length scale reaches either the ion Larmor radius [21,29] or the ion inertial length [8].

The transition from the MHD to kinetic scale is expected to be observed as a gradual steepening of the frequency spectrum. However, a flattening of the profile just prior to the expected spectral break was reported by Chandran *et al.* [30] and was attributed to enhanced activity of kinetic Alfvén waves. Moreover, Neugebauer [31] found a peak at a frequency $f^* = V/2\pi R$, where V is the solar wind speed and R is the Larmor radius corresponding to the proton thermal speed. The peak was ascribed to structures created by the proton gyromotion that are convected along the spacecraft. f^* is tenths of Hz under typical conditions, close to the expected break frequency.

In this Letter, we introduce the *in situ* experiment that allows us to explore the upper end of the kinetic range. Based on a combination of differently oriented Faraday cups, the experiment provides plasma moments with a time resolution of 31 ms. We discuss the first measured power spectra of ion velocity, density, and temperature fluctuations in the solar wind down to the ion kinetic scale.

Instrumentation and examples of frequency spectra.—The bright monitor of solar wind (BMSW) instrument was launched onboard the Spektr-R spacecraft. Unfortunately, the onboard magnetometer is not in operation; thus, we are forced to propagate the magnetic field from other spacecraft (Wind is used in this Letter). However, the present study deals with the frequency spectra computed on long-time intervals, so the lack of magnetic field measurements does not impose notable limitations.

The determination of solar wind parameters by BMSW is based on measurements from six Faraday cups. Three of them are oriented in different directions with respect to the solar wind velocity and are used to determine the ion flux vector. The other three Faraday cups point toward the Sun and are equipped with deceleration grids which provide three points of the ion distribution function. These data are sufficient to estimate the ion speed and temperature [32,33].

The frequency spectra of plasma moments computed for quiet solar wind on November 10, 2011 are shown in Fig. 1. Note that only parts of the spectra that are not spoiled by the instrumental noise are shown. One can see the expected spectral shapes for all the parameters with two different slopes. The heavy lines distinguish the parts of the spectra used for the slope determination; the values of the slopes are given in the figures. The slopes of the low-frequency parts range from -1.37 for the thermal speed to -1.66 for the density. The slope of this part of the velocity spectrum is close to that already discussed, $-3/2$; e.g., Refs. [10–13,34]. The density spectrum exhibits the expected slope of $-5/3$ but careful examination shows a slight flattening at the high-frequency end of the inertial scale (0.1–0.5 Hz) as previously reported and attributed to the compressive turbulence (e.g., Ref. [35]).

The angular ion cyclotron frequency, ω_c, was ≈ 0.46. The break frequency which is the intersection point of the best linear fits to the two parts of the spectrum distinguished in Fig. 1, is close to ω_c for the density spectrum (≈ 0.6 Hz). However, the break frequencies of the bulk velocity and thermal velocity spectra are at significantly lower frequencies than ω_c (0.12 and 0.18 Hz, respectively). The slopes of the high-frequency parts are much steeper than the low-frequency parts and range from -2.6 to -3.9.

Spectral slopes and spectral breaks.—Our first results representing ≈ 20 time intervals with durations from 15 min to 1 h suggest trends for the spectral indices and the break frequency. The criteria for selection of these time intervals were (i) to cover a broad range of solar wind parameters, (ii) to enable reliable determination of slopes and break frequencies, and (iii) constant solar wind and IMF parameters within each time interval. The speed varies from 320 to 635 km/s, the density from 1.5 to 32 cm^{-3} and the IMF magnitude from 4 to 15 nT in our time intervals. The Alfvén speed, proton cyclotron frequency, plasma frequency, Mach number, and proton inertial length were chosen as possible candidates for data organization. These parameters are not independent; thus, the plots of the break frequency and/or slopes versus these parameters exhibit similar features. However, the degree of data organization is different. We show three examples of such plots with a good data organization in Fig. 2. The break frequencies, f_b of all three quantities as a function of the proton cyclotron frequency, f_c can be found in Fig. 2(a). The dotted line stands for $f_b = 2\pi f_c$ and reveals that whereas the break frequency of the density spectra is always larger than the angular cyclotron frequency, the break frequencies of the bulk and thermal speed spectra are lower than that in a systematic manner.

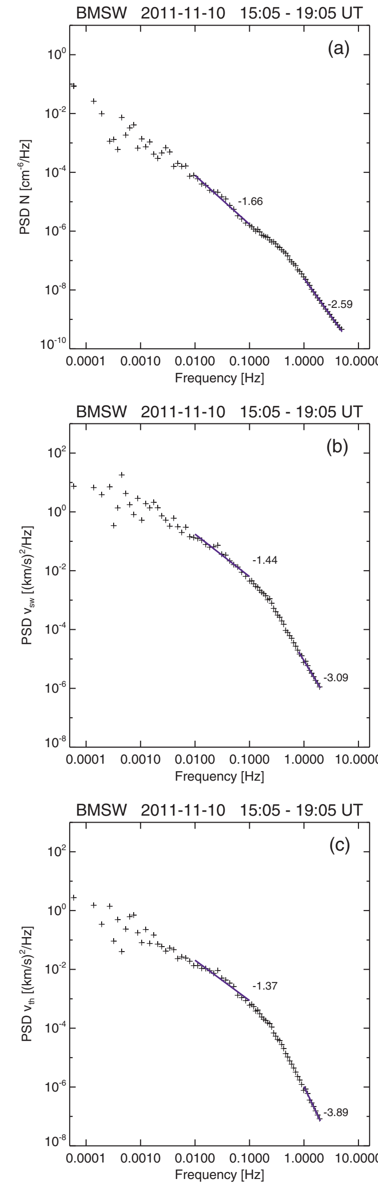

FIG. 1 (color). Power spectra of the ion density, PSD N (a); total ion velocity, PSD v_{SW} (b); and thermal ion speed, PSD v_{th} (c) on November 10, 2011 between $\approx$ 1500 and 1900 UT.

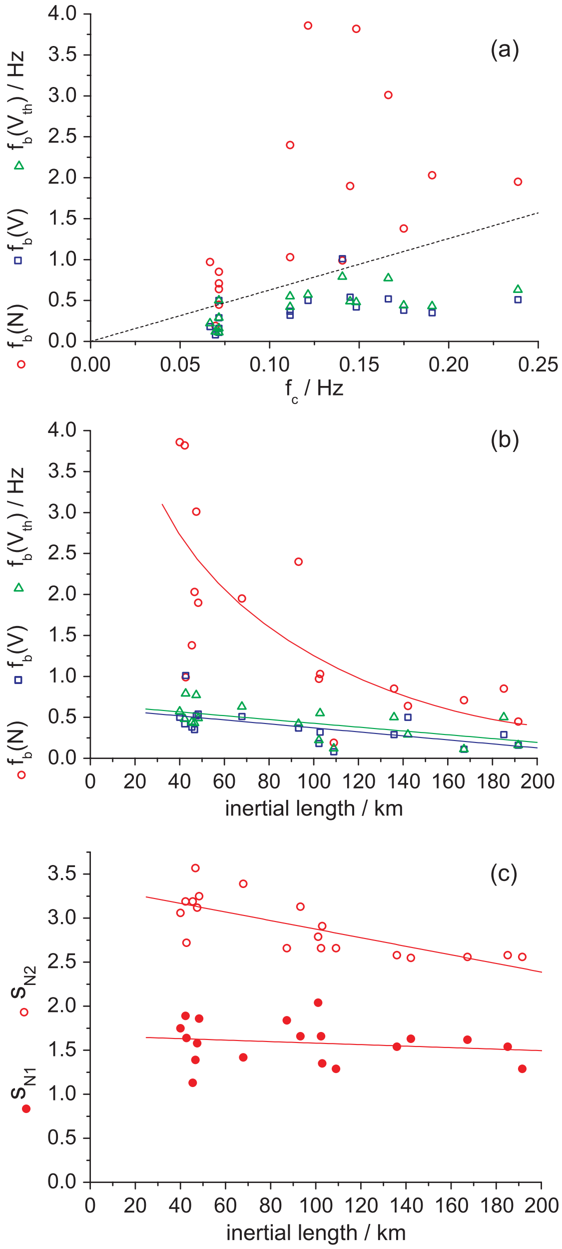

FIG. 2 (color). The dependence of the break frequencies of the ion density $f_b(N)$, the ion velocity $f_b(V)$, and the ion thermal velocity $f_b(V_{\rm th})$ fluctuations on the proton cyclotron frequency f_c (a); the inertial length (b); and the dependence of the slopes of the density spectra in the MHD, S_{N1} and kinetic, S_{N2} scales on the ion inertial length (c).

Figure 2(b) shows the density and speed break frequencies as a function of the ion inertial length. The figure demonstrates clear decreasing trends that suggest that the spatial inhomogeneities are probably a major source of the fluctuations. Figure 2(c) presents the spectral slopes of the density fluctuations as a function of the inertial length. The plot shows that whereas the spectral slope at the MHD (S_{N1}) scale is constant with a mean value of ≈ 1.6, the spectrum corresponding to the kinetic

TABLE I. Average slopes (from 20 cases) in the MHD and kinetic scales and the average value of the break frequency, f_b.

MHD scale, slope			Kinetic scale, slope			Break frequency, f_b/Hz		
S_{N1}	S_{V1}	$S_{V\rm th1}$	S_{N2}	S_{V2}	$S_{V\rm th2}$	$f_b(N)$	$f_b(V)$	$f_b(V_{\rm th})$
1.59	1.45	1.45	2.90	3.37	3.45	1.59	0.38	0.44

(S_{N2}) scale seems to become harder for shorter inertial lengths.

Discussion and conclusion.—We present an analysis of the frequency spectra of the solar wind turbulence. Table I summarizes the average values of spectral indices and the break frequency. The indices of the density spectra (−1.6 at MHD and −2.9 at ion scales) are comparable to those observed for magnetic field (e.g., Refs. [8,15,17]) and electron density [28] fluctuations and thus the broad discussion of the origin of these indices in Chen *et al.* [28] can be applied.

The fluctuations of the bulk and thermal speeds are similar to each other but the spectral indices differ from those determined for the density fluctuations. The gradual slope of (−1.45) for the speed spectrum at the MHD scale is consistent with the finding of Podesta *et al.* [9]. These are the first measurements of the bulk and thermal speed fluctuations at the ion kinetic scale and we find a steeper spectrum at this scale with a mean slope for both of about −3.4. The differences between the density and speed spectral indices result in the different break frequencies. We compared these frequencies with the proton angular cyclotron frequency in Fig. 2(a) and found that the break frequency of the density spectra is higher than the angular cyclotron frequency, whereas that of the speed spectra is lower. This difference suggests that dissipation of compressible fluctuations that survive toward higher frequencies is reduced. The decrease of the break frequencies with the inertial length indicates that the spatial variations of all quantities that are convected by the spacecraft are important constituents of the turbulence.

Figure 2 reveals a large spread of the spectral indices as well as the break frequencies. This spread could be real variability but we think that some of this variability is an artifact of the calculation. Most spectra exhibit a plateau near the break frequency, so we must choose which part of the spectrum should be used for the slope determination. Moreover, the plateau often exhibits a positive slope as Fig. 3 demonstrates. Such a broad peak in the spectrum of magnetic field fluctuations was described in Eastwood *et al.* [36] and attributed to the foreshock waves. Nevertheless, Fig. 3(c) shows a similar peak in the spectrum of magnetic field fluctuations from a corresponding interval of Wind IMF measurements. Since Wind was near the L1 point, the foreshock effects can be ruled out and we search for other possible sources.

Neugebauer [31] suggested a peak of the magnetic field spectrum at the frequency $f^* = 0.7$ Hz for the case in

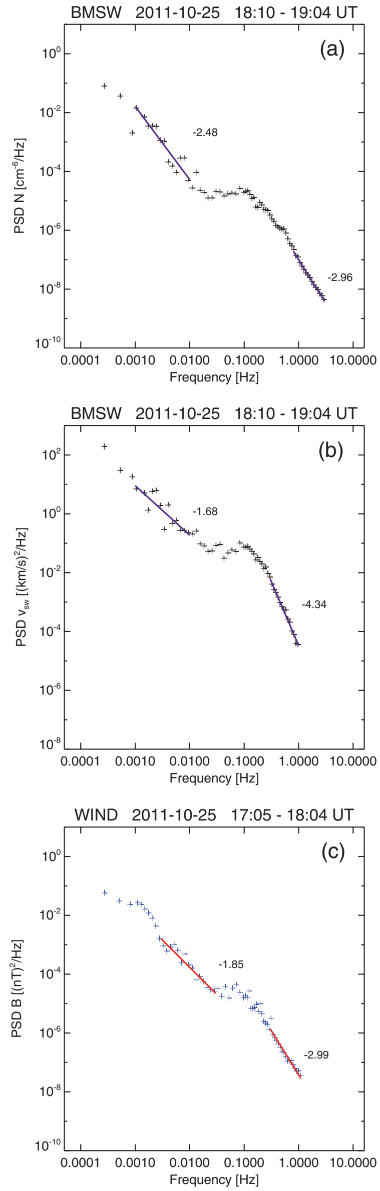

FIG. 3 (color). Power spectra of the ion density (a); the total ion velocity (b); and the magnetic field (c) fluctuations on October 25, 2011. The magnetic field fluctuations are from Wind.

Fig. 3 but the enhancement is observed at ≈ 0.2 Hz. A quantitative comparison with Chandran *et al.* [9] who attributed the plateau to kinetic Alfvén waves is difficult because only spacecraft frame frequencies are known. Although an explanation of a bump in terms of excitation of new waves seems to be natural, we suggest that this bump is caused by enhanced damping of the fluctuations within the MHD scale because the slope of this part is much steeper than values shown in Table I. Finally, we should point out that (i) the spectra such as shown in Fig. 3 occur frequently an that (ii) these spectra were not used in the statistics shown in Fig. 2 and Table I.

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