Large-scale Control of Kinetic Dissipation in the Solar Wind

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Received 2018 June 13; revised 2018 July 6; accepted 2018 July 11; published 2018 August 6

Abstract

In this Letter, we study the connection between the large-scale dynamics of the turbulence cascade and particle heating on kinetic scales. We find that the inertial range turbulence amplitude (|dB|) measured in the range of 0.01–0.1 Hz is a simple and effective proxy to identify the onset of significant ion heating, and when it is combined with β||/βp, it characterizes the energy partitioning between protons and electrons (T_p/T_e); proton temperature anisotropy (T_⊥/T_∥); and scalar proton temperature (T_p) in a way that is consistent with previous predictions. For a fixed |dB|, the ratio of linear to nonlinear time scales is strongly correlated with the scalar proton temperature in agreement with Matthaeus et al., though for solar wind intervals with β|| > 1, some discrepancies are found. For a fixed |dB|, an increase of the turbulence amplitude leads to higher T_p/T_e ratios, which is consistent with the models of Chandran et al. and Wu et al. We discuss the implications of these findings for our understanding of plasma turbulence.

Key words: magnetohydrodynamics (MHD) – plasmas – solar wind – turbulence – waves

1. Introduction

The solar wind is ubiquitously observed to be in a turbulent state with a power spectrum of fluctuations spanning from magnetohydrodynamic to smaller kinetic scales (e.g., Coleman 1968; Siscoe et al. 1968). Between approximately 10^{-4} and 0.3 Hz in the spacecraft frame, the magnetic fluctuations form a power law called the inertial range, which is characterized with a spectral index of -5/3 corresponding to the fluid scaling (e.g., Podesta 2009; Horbury et al. 2012). At approximately f_w = 0.3 Hz, the spectrum steepens and energy starts to dissipate leading to particle heating (e.g., Leamon et al. 1998; Bruno & Carbone 2005; Howes et al. 2008). In the sub-ion range, the turbulence has Alfvénic nature (Chen et al. 2013) and the spectrum has a clearly non-universal spectral index in the range of -4 to -2 (e.g., Leamon et al. 1999; Sahraoui et al. 2010), which has been found to be correlated with the energy cascade rate (e.g., Smith et al. 2006; Matthaeus et al. 2008). The partitioning of the dissipated energy between protons and electrons is thought to be affected by several plasma parameters, including the nonlinear timescales (Matthaeus et al. 2016), gyroscale turbulence amplitude (Chandran et al. 2010), and the ratio of parallel thermal pressure to magnetic pressure (Cerri et al. 2017): β||/βp = 2μ_p n_p k_p T_p / B_0^2.

A crucial factor characterizing the energy cascade rate and the relative heating of protons and electrons is the nonlinear timescale at which the energy is transferred to smaller scales (see review by Horbury et al. 2012). Goldreich & Sridhar (1995) proposed the critical balance theory predicting that the linear timescale corresponding to the propagating Alfvénic fluctuations and their nonlinear decay are comparable at each scale: τ_A(k_i) ~ τ_CB(k_i), where k_i is the perpendicular (with respect to the magnetic field) wavenumber. The Alfvén time and the nonlinear “critical balance” time are estimated for a given spatial scale perpendicular to the background magnetic field (λ ~ 2π/k_i) as

τ_A(λ) ~ l_∥ / V_A ~ (L / λ)^{1/3} λ / V_A,

τ_CB(λ) ~ λ / δξ_A,

where l_∥ is the spatial scale along the magnetic field, V_A is the Alfvén speed (B_0/(ρμ_0)^{1/2}), L is the size of the outer scale of the cascade, and δξ = δv + δb, δv, and δb are the Elsässer, velocity, and magnetic fluctuations at scale λ, respectively. The perpendicular scale of the eddies decreases at a faster rate than the parallel scale, with the scaling k_∥ ~ k_⊥^{3/2}. Both observational (e.g., Horbury et al. 2008; Podesta 2009; Wicks et al. 2010; Chen et al. 2011) and numerical (e.g., Cho & Vishniac 2000; Maron & Goldreich 2001; TenBarge & Howes 2012) studies are consistent with critical balance scalings; see Chen (2016) for a detailed review.

In contrast to critical balance theory, Matthaeus et al. (2014) argued that the most significant contributions to nonlinear spectral transfer are independent of τ_A. They proposed that at kinetic scales the relevant timescale ratio is between the gyroperiod, τ_ci ~ Ω_c^{-1}, and nonlinear turnover time (e.g., the time it takes until an eddy at scale l passes all of its energy to a smaller scale) at scale l ~ d_l,

τ_ml(d_l) = V_A / [ZΩ_c (d_l / d_i)^{1/3}],

which determines how the dissipated energy is partitioned in proton and electron heating (Q_p/Q_e ~ 1/(τ_mlΩ_c)). The ion inertial length is d_l = c / ω_p, ω_p = √(n_i q_i^2 / ε_0 m_i) is the ion plasma frequency, and Ω_c = q_B_0 / m_p is the proton gyrofrequency. The total energy per unit mass is given as Z = √(u^2 + b^2), where u and b denote the root-mean-square
velocity and magnetic field fluctuations, the latter measured in velocity units \( b = b_{\text{rms}} \sqrt{\rho_0/\rho} \).

In addition to the nonlinear timescales, the magnitude of the gyroscale velocity fluctuations also plays an important role in controlling the proton and electron heating. When the electromagnetic field fluctuations at gyroscale surpass a critical amplitude, the first adiabatic invariant of particle motion is not conserved allowing perpendicular heating of the particles known as stochastic ion heating (e.g., McChesney et al. 1987; Johnson & Cheng 2001). Chandran et al. (2010) proposed that stochastic heating depends on the dimensionless parameter \( \epsilon = \delta v_p/v_i \), where \( \delta v_p \) is the root-mean-square velocity fluctuations at gyroscale and \( v_i \) is the ion’s thermal speed perpendicular to the magnetic field. The perpendicular proton heating rate per unit mass \( (Q_\perp) \) at \( k_L \rho_p \sim 1 \) (where \( \rho_p = \rho_{th, pi}/\Omega_i \) is the proton gyroscale) as a fraction of the turbulent cascade power per unit mass \( (\Gamma) \), assuming a balanced spectrum of kinetic Alfvén waves (KAWs) can be given in the form of

\[
Q_\perp / \Gamma = 3.0 \exp \left( -0.34 / \epsilon \right). \tag{4}
\]

Equation (4) implies that half of the total cascade power is directed into perpendicular proton heating at \( k_L \rho_p \sim 1 \), when \( \epsilon = 0.19 \).

Another significant parameter affecting the dissipation process is \( \beta_{fl} \), which enhances or completely restricts the operation of certain heating mechanisms. When \( \beta_{fl} \ll 1 \), electron Landau damping dominates, while proton Landau damping is negligible because the thermal ions are too slow to satisfy the Landau resonance condition (Quataert 1998). On the other hand, when \( \beta_{fl} \sim 1 \), Landau and transit time damping of KAWs lead to significant parallel proton heating (Gary & Nishimura 2004). Heating due to reconnection may also depend on \( \beta_{fl} \), Mistry et al. (2017) found that the temperature increase of the exhaust region is a function of the inflow, \( \beta_{fl} \), and reconnection guide field. The onset of stochastic heating is thought to be independent of \( \beta_{fl} \) for \( \beta_{fl} \lesssim 1 \) (Chandran et al. 2010).

Electron and proton heating by solar wind turbulence has been investigated by both observational (e.g., Cranmer et al. 2009; Coburn et al. 2012; He et al. 2015; Hellinger et al. 2011; Narita & Marsch 2015; Sorriso-Valvo et al. 2018) and numerical studies (e.g., Breech et al. 2009; Servidio et al. 2012; Wan et al. 2015, 2016; Gary et al. 2016; Valentini et al. 2016; Yang et al. 2017). Wu et al. (2013) used particle-in-cell simulation in the presence of a strong magnetic field to study how the decaying energy in the turbulent cascade is partitioned between protons and electrons, and they concluded that as the turbulence energy increases, protons are heated more. The crossover value \( (T_p = T_e) \) occurred when the initial turbulence amplitude \( \delta B/B_0 \) reached 2/5. They suggested that the correlation between the proton heating and turbulence amplitude is primarily due to the increased involvement of coherent structures in the kinetic processes (e.g., Parashar et al. 2009; Markovskii & Vasquez 2010; Greco et al. 2012; Chasapis et al. 2017).

Cerri et al. (2017) compared a 2D hybrid Vlasov–Maxwell simulation of externally driven turbulence and a hybrid 2D particle-in-cell simulation of freely decaying turbulence. Despite the fundamental differences between the two simulations, the kinetic scale turbulence was remarkably similar: the root-mean-square amplitudes of the density, parallel, and perpendicular magnetic field fluctuations showed less than a factor of two difference, and depended only on \( \beta \). Cerri et al. (2017) concluded that regardless how the large-scale fluctuations are injected, the system continuously “reprocesses” the turbulent fluctuations as they are cascading toward smaller scales and the response of the system is primarily driven by \( \beta \).

In this Letter, we continue this general line of inquiry and study how the dissipated energy is partitioned between protons and electrons in the solar wind as a function of the strength of the cascade. To quantify the strength of the cascade, we use a directly measurable proxy, the average inertial range amplitude \( (\delta B_i) \) of the turbulence spectrum of magnetic fluctuations. We find that the \( (\beta_{fl}, \delta B_i) \) space organizes the solar wind plasma measurements in a way that is consistent with current theories about solar wind heating in particular with Chandran et al. (2010), Wu et al. (2013), and Matthaeus et al. (2016), and characterizes the proton–electron temperature ratio \( (T_p/T_e) \), the proton temperature anisotropy \( (T_{pi}/T_{pe}) \), and the scalar proton temperature \( (T_p) \). Finally, we aim to identify the timescale ratio that has the best correlation with \( T_p \). For this purpose, we test \( \tau_{ci}/\tau_{ci}(d_i) \), \( \tau_{\alpha}(\rho_p)/\tau_{ci}(\rho_p) \), and a “hybrid” timescale ratio defined as \( \tau_{\alpha}(\rho_p)/\tau_{ci}(\rho_p) \times \exp(-0.34/\epsilon) \) incorporating the effect of stochastic ion heating.

2. Method

We selected Wind magnetic field (Lepping et al. 1995; 92 ms cadence), ion (SWE FC, 92 s cadence), and electron (45 s cadence) data (Lin et al. 1995; Ogilvie et al. 1995) from 2004 January to 2016 December, and split the timeseries into 10-minute intervals. For each of the \( ~5.8 \times 10^7 \) intervals, \( T_i \), \( T_e \) (with orientations defined based on the average magnetic field direction during each 92 s interval), \( \beta_{fl} \), and \( T_e \) were averaged. The power spectral density (PSD) of the magnetic field components were calculated separately via Fourier transform, and the component PSDs were summed up to obtain the total PSD (Koval & Szabo 2013). The spectral index in the inertial range was calculated by fitting the PSD between 0.01 and 0.1 Hz; \( \delta B_i \) corresponds to the average (in log space) power level measured in this frequency range. The average and standard deviation of the measured spectral indices are \(-1.68 \pm 0.26\), respectively, and are in excellent agreement with previous studies (e.g., Leamon et al. 1999; Smith et al. 2006; Alexandrova et al. 2009).

To estimate \( \tau_{\alpha} \) (Equation (1)) and \( \tau_{nl} \) (Equation (3)), we assume that the spectral break between the outer and inertial ranges of the turbulence cascade is at a constant frequency of \( 10^{-4}\) Hz (e.g., Podesta 2009; Wicks et al. 2011) and calculate the size of the outer scale \( L \) as \( V_{sw}/(2\pi \times 10^{-4}) \), where \( V_{sw} \) is the solar wind speed. Matthaeus et al. (2014) suggested that under typical solar wind conditions, \( Z/V_{\alpha} \) is expected to be in the range of 0.5–1. We calculated \( Z \) based on the root-mean-square velocity and magnetic field fluctuations during each 10-minute interval, and found that the median \( Z/V_{\alpha} \) ratio is 0.42.

Measuring the gyroscale velocity fluctuations with current instruments, is only possible under exceptional solar wind conditions. To be able to conduct a statistical study, we use the approach of Bourouaine & Chandran (2013) to estimate \( \delta v_p \) in Equation (2) based on the spectrum of magnetic field fluctuations as \( \delta v_p = \sigma V_N \delta B/B_0 \), where \( \sigma = 1.19 \) is a dimensionless constant arising from the kinetic Alfvén dispersion relation, and \( \delta B \) is the gyroscale turbulence amplitude. For details of the technique and its application for a statistical
The Astrophysical Journal Letters, 863:L4 (6pp), 2018 August 10

Vech, Klein, & Kasper

study, see Bourouaine & Chandran (2013) and Vech et al. (2017). For the calculation of \( \delta b \) in Equation (2), we used the gyroscale turbulence amplitude expressed in Alfvén units: 
\[
\delta b = \delta B / (\mu_0 \rho)^{1/2}.
\]

3. Results

The distributions of \( T_p \), \( T_T / T_H \) and \( T_e \) were studied in 2D histograms with 50 \( \times \) 50 logarithmically spaced bins in the \( (\beta_{||}, \delta B) \) space. The median of each bin was selected, and sparse bins with fewer than 10 data points were discarded. In our data set, the medians of \( \beta_{||} \) and \( \delta B_i \) are 0.99 and 0.72 nT\(^2\) Hz\(^{-1}\), respectively.

The scalar proton temperature in Figure 1(a) increases as a function of \( \delta B_i \), and when \( \delta B_i \) is larger than 0.2 nT\(^2\) Hz\(^{-1}\), the peak temperature is around 4 \( \times \) 10\(^5\) K, while for \( \delta B_i < 0.1 \) nT\(^2\) Hz\(^{-1}\), the temperature is around 3 \( \times \) 10\(^4\) K. The \( \delta B \) dependence of the scalar proton temperature is shown in Figure 2(a) for three values of \( \beta_{||} \) as dashed lines; in all cases, the temperature increases nearly exponentially as a function of \( \log_{10} \delta B_i \).

In Figure 1(b), the proton temperature anisotropy is significantly different for the \( \beta_{||} < 1 \) and \( \beta_{||} > 1 \) regions: for small \( \beta_{||} \), the anisotropy increases as a function of \( \delta B_i \), while for large \( \beta_{||} \) no obvious systematic trend can be seen. In Figure 2(b), the temperature anisotropy for \( \beta_{||} = 0.2 \) is nearly constant when \( \delta B_i < 0.2 \) nT\(^2\) Hz\(^{-1}\), while for \( \delta B_i > 0.2 \) nT\(^2\) Hz\(^{-1}\) there is a clear indication of perpendicular proton heating \( (T_T / T_H \sim 1.15) \). In the case of \( \beta_{||} = 1 \), for low \( \delta B_i \) values, minor parallel heating is observed \( (T_T / T_H \sim 0.95) \) and the temperature anisotropy reaches unity in the high \( \delta B_i \) limit.

In Figure 1(c), the \( T_e \) distribution shows positive correlation with \( \delta B_i \) and the \( T_e \) values change with approximately a factor of three across the whole range of \( \delta B_i \). In Figure 2(a) when \( \delta B_i < 0.4 \) nT\(^2\) Hz\(^{-1}\), \( T_p / T_e < 1 \), while for the largest \( \delta B_i \) values, the relation becomes \( T_p / T_e \approx 1 \).

Figure 1. Median values of the scalar proton temperature (a), proton temperature anisotropy (b), and electron temperature (c), in the \( (\beta_{||}, \delta B) \) space.

Figure 2. (a) Cross-sections of Figures 1(a) (dashed lines) and (c) (solid lines) along \( \beta_{||} = 0.2, 1 \) and 2, respectively. (b) Cross-section of Figure 1(b) along \( \beta_{||} = 0.2, 1 \) and 2, respectively.
values, the protons have a factor of 2.5 higher temperature than electrons. It is important to note that the proton–electron temperature equilibrium shows significant dependence on $\beta_{||p}$; as $\beta_{||p}$ changes from 0.2 to 2, the $\delta B_i$ value corresponding to $T_p = T_e$ significantly decreases, meaning that in a plasma with high $\beta_{||p}$ even relatively small magnetic fluctuations are sufficient to produce equal proton and electron temperatures.

In Figure 3, we calculate the value of three timescale ratios, $\tau_{ci}/\tau_{nl}$ (a), $\tau_A/\tau_{CB}$ (b), and $\tau_A/\tau_{CB}(\rho_p) \times \exp(-0.34/\epsilon)$ (c) in the $(\beta_{||p}, \delta B_i)$ space. As expected, the distribution of all three ratios show similarities to the proton temperature shown in Figure 1(a). The correlation between Figures 3 and 1(a) is weakest in the region where $\delta B_i \in [0.01; 3] \text{nT}^2 \text{Hz}^{-1}$ and $\beta_{||p} > 1$. For a fixed $\beta_{||p}$ value, there is positive correlation between proton temperature and the timescale ratios, which is in qualitative agreement with the prediction of Matthaeus et al. (2016). To estimate the uncertainties in Figure 3 we computed the ratio of the standard deviation and mean in each bin. The average uncertainties are 29%, 25%, and 34% for Figures 3(a–c), respectively. We note that the errors are the lowest (below 10%) for $\beta_{||p} > 1$, and $\delta B_i > 0.1 \text{nT}^2 \text{Hz}^{-1}$.

To quantify the correlation between the three distributions in Figure 3 with Figure 1(a), we use the Spearman’s rank correlation ($R_S$), which measures how well the relationship between the timescale ratios and $T_p$ can be described with a monotonic function. The correlations between the binned timescale ratios and $T_p$ are $R_S = 0.83$, $0.82$, and $0.88$ for $\tau_{ci}/\tau_{nl}$, $\tau_A/\tau_{CB}$, and $\tau_A/\tau_{CB}(\rho_p) \times \exp(-0.34/\epsilon)$, respectively. We are therefore unable to distinguish between the predictive power of these timescale ratios in determining $T_p$.

As $T_p \sim \beta_{||p}B^2 \sim \beta_{||p}\delta B_i$, the proton temperature distribution may simply be a linear function of the abscissa and ordinate variables of Figure 1. To test this dependence, we binned

Figure 3. Median values of $\tau_{ci}/\tau_{nl}$ (a), $\tau_A/\tau_{CB}(\rho_p)$ (b), and $\tau_A/\tau_{CB}(\rho_p) \times \exp(-0.34/\epsilon)$ (c) in the $(\beta_{||p}, \delta B_i)$ space.

Figure 4. Median values of the $T_{\text{predicted}}/T_{\text{true}}$ ratios in the $(\beta_{||p}, \delta B_i)$ space testing the $\beta_{||p}\delta B_i \sim T_p$ scaling. The contour indicates the $T_{\text{true}} = T_{\text{predicted}}$ boundary.
0.03 × β̃_pδB_i as a function of the (β̃_p, δB_i); the factor of 0.03 Hz corresponds to the center (in log space) of the frequency range where δB_i is measured. The values of 0.03 × β̃_pδB_i data were multiplied with a constant factor of 5.9 × 10^3, so it had the same mean as the mean of the observed proton temperature. Finally, a least-square fit (y = 0.201x + 4.258) was made between the logarithm of 0.03 × β̃_pδB_i (x) and logarithm of the actual proton temperature (y) data. If the linear β̃_p and δB_i dependencies are the only significant factors in the behavior of T_p®, then we expect that the predicted proton temperature (T_ppredicted) based on the power-law fit to agree well with the the observed proton temperature (T_observ). Figure 4 shows the ratio T_ppredicted/T_observ in the (β̃_p, δB_i) space. Three major features can be observed: for β̃_p < 1 and δB_i < 0.2 nT^2 Hz^-1, the observed proton temperature is lower than the predicted values with a factor of 1.5, while for δB_i > 0.2 nT^2 Hz^-1 the observed temperature is higher by a factor of two. The discrepancy is the most significant for high β̃_p, where the observed temperature is a factor of three lower than the predicted one. This is also the region with the lowest correlation between the timescale ratios and T_p®. Therefore, we conclude that the naive T_p® ~ β̃_pδB_i scaling is not sufficient to explain the variability of the T_p® distribution in Figure 1(a).

4. Conclusion

In this Letter, we have studied the connection between the inertial range of the turbulent cascade and the small scale dissipation in the solar wind as function of the inertial range turbulence amplitude δB_i and β̃_p. Our approach links directly the characteristics of the turbulence spectrum of magnetic fluctuations to heating mechanisms on kinetic scales, and therefore it could be potentially a simple and effective tool to diagnose heating in the solar wind and in plasma systems more generally.

Vech et al. (2017) identified the onset of stochastic heating when ε = δB_i/ν_L reached 0.025, and 76% of the studied intervals had an ε value larger than this. Here, we used the exact same time interval allowing a direct comparison between ε and δB_i; when δB_i is in the range of 0.1–0.3 nT^2 Hz^-1 (e.g., approximately where the sudden perpendicular temperature enhancement is observed in Figure 2(b)), the median ε is 0.029, and 74% of the intervals had an δB_i value larger than 0.3 nT^2 Hz^-1. Due to this excellent agreement between critical values of ε and δB_i, we interpret the sudden enhancement of T_i/T_L as the onset of stochastic ion heating. The evolution of the temperature parameters in Figures 1–2 across a critical threshold of turbulence amplitude is in qualitative agreement with the stochastic ion heating model of Chandran et al. (2010).

We note that the model of Chandran et al. (2010) was parameterized for gyroscale velocity fluctuations to identify the critical turbulence amplitude when the gyromotion of protons is disrupted. Our findings suggest that stochastic heating is controlled by large-scale dynamics of the turbulent cascade and that reaching the critical turbulence amplitude at gyroscale is a direct consequence of the increased energy cascade rate from larger scales.

For a fixed β̃_p, the T_p®/T_e ratio increases as a function of δB_i. When the turbulence amplitude is small (δB_i < 0.3 nT^2 Hz^-1), electrons are hotter, while for larger turbulence amplitudes T_p®/T_e > 1. As β̃_p increases T_e occurs at smaller δB_i meaning that in a high β̃_p plasma even relatively small turbulence amplitudes can lead to equal proton and electron temperatures. These findings may be especially relevant for astrophysical plasmas where β_p ≫ 1. Our results are in qualitative agreement with the predictions of Wu et al. (2013), however we note that the increased proton temperatures as a function of δB_i may be partially caused by stochastic ion heating, the effects of coherent structures in the proton heating, or both mechanisms.

The timescale ratios had similar distributions in the (β̃_p, δB_i) space and they all had strong correlation with the proton temperature data (0.88 > R_p > 0.82), thus in our data they are indistinguishable. For a fixed δB_i value, the T_p®/T_e ratio increases as a function of all the timescale ratios, which is consistent with the prediction of Matthaeus et al. (2016). The weakest correlation between the timescale ratios and T_p® was observed for high β̃_p.

Finally, Cerri et al. (2017) suggested that the response of a plasma system is primarily driven by the amount of available energy at kinetic scales and β̃_p. Our findings are in agreement with this concept, and β̃_p may have the most significant influence on the proton–electron temperature ratio by restricting and enhancing the operation of certain heating mechanisms.

K.G. Klein was supported by NASA grant NNX16AM23G. J.C. Kasper was supported by NASA grant NNX14AR78G. Data were sourced from CDAWeb (http://cdaweb.gsfc.nasa.gov/).

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