Observation of Kolmogorov Turbulence in the Jovian Magnetosheath From JADE Data

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Abstract Power spectra of magnetic-field fluctuations near Jupiter have been analyzed since the early days of space exploration with Voyager and Ulysses flyby of Jupiter. Power spectra of velocity and density fluctuations, however, have not been as well studied, due to the lack of high-resolution measurements required to resolve a significant fraction of the inertial range. Here, we investigate fluid-scale turbulence in Jupiter's magnetosheath using measurements from the Jovian Auroral Distributions Experiment (JADE) instrument onboard Juno spacecraft. Both ion density and velocity spectra exhibit nearly Kolmogorov scaling \( \sim f^{-5/3} \). This indicates weakly compressible fluctuations and the presence of a scale-invariant cascade through the inertial range. Although this is a specific case study and not necessarily representative of the overall behavior, our result shows that Alfvénic Kolmogorov-type turbulence exists in at least some locations in Jupiter's magnetosheath.

Plain Language Summary The classical theory of turbulence, given by Kolmogorov in 1941, predicts that the size scales of various turbulent structures follow a specific pattern, with more power held in larger turbulent structures. The region where the Sun's outflowing plasma—the solar wind—is diverted around Jupiter's magnetic environment, is called the magnetosheath. Using NASA's Juno mission data, we show for the first time that the ion fluctuations in Jupiter's magnetosheath region follow the expected pattern of power in different spatial scales. This result indicates that fully developed turbulence, consistent with classical (Kolmogorov) turbulence theory, is present in Jupiter's magnetosheath. We also characterize the size of the large-scale turbulent structures in the system. These results provide insights into the nature of plasma turbulence in other similar astrophysical systems.

1. Introduction

The solar wind is the supersonic outward flow of plasma from the Sun. When the turbulent solar wind approaches Jupiter, it crosses a bow shock, which slows the plasma to subsonic speeds and causes significant increase in the plasma's density, temperature, and turbulence level. This region of subsonic plasma between the bow shock and magnetosphere is known as the magnetosheath. Magnetosheath of different sizes with varying properties is seen in the magnetospheres of Earth, Saturn, and Jupiter (Bagenal et al., 2017). The bounding surface of the magnetosphere is called the magnetopause. The magnetopause is the region where the source of the magnetic field changes: inside the magnetopause, the controlling magnetic field is that of Jupiter; while outside, it is the solar wind magnetic field.

The magnetosheath is the interface of the solar wind-magnetosphere interaction, affecting the physical processes occurring within Jupiter's magnetopause. The magnetosheath magnetic field and plasma interact at the magnetopause and, consequently, with Jupiter's magnetosphere (Ranquist et al., 2020). Therefore, studying the properties of turbulence in the magnetosheath helps to better understand the dynamical coupling between the solar wind and the magnetosphere and to improve the current models. In addition, the interest in exploring plasma turbulence near Jupiter also lies in its plasma conditions: it has a strong magnetic field, a broad range of plasma \( \beta \) (the ratio of thermal pressure to magnetic pressure) values (Ranquist et al., 2019), and a very large system size, the combination makes the Jovian magnetospheric system a
unique system, that is, distinct from the near-Earth space and even the Saturn’s magnetosphere (McComas & Bagenal, 2007; Bagenal et al., 2017).

Most solar, heliospheric, and astrophysical plasmas exist in some level of a turbulent state (Matthaeus & Velli, 2011). The turbulent fluctuations in these magnetized plasmas play a fundamental role in heating and accelerating charged particles, thus affecting the dynamics of plasmas (Bandyopadhyay, Matthaeus, Chasapis, et al., 2020; Bandyopadhyay, Matthaeus, Parashar, Chhiber, et al., 2020; Bandyopadhyay, Matthaeus, Parashar, Yang, et al., 2020; Tessein et al., 2013; Yang et al., 2017). Among the various naturally occurring plasmas, the solar wind and planetary magnetosheaths are highly accessible “laboratories” for studying the properties of plasma turbulence (Bruno & Carbone, 2013). The nature of turbulent fluctuations across different range of spatial and temporal scales provides key inputs for transport models (Miesch et al., 2015). The results obtained in these systems allow understanding turbulence processes in other collisionless magnetized plasmas more generally. Moreover, the fact that the magnetosheath is a bounded region on one side by the bow shock, and on the other side by the magnetopause makes it useful to study the effect of large scales boundaries on the nature of the turbulence properties and to study the evolution of turbulence in a confined space (Huang et al., 2017; Rakhmanova et al., 2020). Here, we use state-of-the-art plasma data from the Jovian Auroral Dynamics Experiment (JADE, McComas, Alexander, et al., 2017) and magnetometer data (Connerney, Benn, et al., 2017) on NASA’s Juno spacecraft (Bolton et al., 2017) to study the turbulence processes in Jupiter’s magnetosheath and compare them with the turbulence properties in the solar wind and the magnetosheath of Earth and Saturn.

Turbulence is a multi-scale phenomenon, with a vast range of spatial and temporal scales (Verscharen et al., 2019). A defining feature of turbulence is the formation or presence of randomly moving structures (e.g., swirls or “eddies”) on a variety of size scales. The relative distribution of energy in these structures is quantified by the power spectrum (Coleman, 1968). The power spectrum describes the decomposition of a fluctuating field into various wavenumber (k) components—that is, it partitions the fluctuation “power” of the field into eddies, with the characteristic size of an eddy being 1/k.

The Kolmogorov theory of incompressible hydrodynamic turbulence predicts a k^{−5/3} power law in the inertial range of scales (Kolmogorov, 1941). Spectral indices close to the Kolmogorov scaling have been routinely observed in the solar wind (Bale et al., 2005; Bandyopadhyay, Chasapis, Chhiber, Parashar, Maruca, et al., 2018; Bandyopadhyay, Chasapis, Chhiber, Parashar, Matthaeus, et al., 2018), interstellar medium and other astrophysical systems (Armstrong et al., 1981; Zhuravleva et al., 2019), terrestrial (Bandyopadhyay, Chasapis, Chhiber, Parashar, Maruca, et al., 2018; Bandyopadhyay, Chasapis, Chhiber, Parashar, Matthaeus, et al., 2018; Huang et al., 2017) and extraterrestrial magnetospheres (Hadid et al., 2015; Tao et al., 2015; Xiao et al., 2018). However, a spectral analysis of the density and velocity fluctuations in the Jovian magnetosheath, especially resolving the inertial range, to our knowledge has not been reported.

Here, we study the signatures of magnetohydrodynamic (MHD)-scale turbulence in Jupiter’s magnetosheath. We find both ion density and velocity spectra are close to Kolmogorov −5/3 scaling, consistent with the theoretical expectation for fully developed, weakly incompressible turbulence.

2. In-Situ Measurements

The Juno spacecraft first encountered Jupiter’s bow shock and crossed into the Jovian magnetosheath on June 24, 2016 (Connerney, Adriani, et al., 2017; McComas, Szalay, et al., 2017). Subsequently, the spacecraft completed a series of 53-days polar orbits with its apojoves (farthest distance from Jupiter in its orbit) at 113 Jovian radii on Jupiter’s dawn side. These orbits provide a first opportunity to study the detailed turbulence properties in Jupiter’s dawn-side magnetosheath (Ebert et al., 2017; Gershman et al., 2017; Hospodarsky et al., 2017; Ranquist et al., 2019) across magnetic and plasma observations. Although some of the previous missions, such as Ulysses, provide some observations of magnetopause—magnetosheath boundary layer turbulence, those are mostly based on magnetic field data (e.g., Tsurutani et al., 1993). Here, we analyze the ion density and velocity turbulence spectra of a magnetosheath sample observed by Juno in the dawnside of the magnetosheath.
We use data obtained during a Jovian magnetosheath crossing on February 20, 2017 (2017-051 using the notation year-DOY) from 01:00:23 to 23:09:54 UTC at a distance of \( \sim 105 R_J \) (\( R_J \) is the Jovian Radii, taken here to be \( R_J = 71,492 \text{ km} \)) from Jupiter. The contextual plot of the particular Juno orbit along with the nominal magnetosheath is shown in Figure 1. We have calculated the bow shock and magnetopause location using the 75th percentile in the (Joy et al., 2002) model. Therefore, about 75% of the samples, analyzed by Joy et al. (2002), would lie within the bow shock and magnetopause used. We use the Jupiter-Sun-Orbit (JSO) coordinate system, where, the \( X_{JSO} \) axis is the unit vector from the center of Jupiter to the Sun, the \( Y_{JSO} \) axis is the unit vector opposite that of Jupiter’s motion around the Sun, and the \( Z_{JSO} \) axis completes the right-handed coordinate system (Bagenan et al., 2017). In SPICE, this JSO is the JUNO_JSO frame.

JADE (McComas, Alexander, et al., 2017) consists of two electron spectrometers and a time-of-flight (TOF) ion instrument, JADE-I, which is used for this study. The JADE-I sensor measures the ion distributions (dominated by protons in the magnetosheath) in the energy range of 0.01–46 keV/q over 64 energy steps, each with an energy resolution \( \Delta E/E \) of 18%–28%. Juno is a spinning spacecraft with a spin period of \( \sim 30 \text{ s} \). During JADE-I’s high-rate mode, a record of 64 energy steps over 12 look directions is taken every 2 s, while during the low-rate modes, records of 64 energy steps by 78 look directions typically take 30, 60, 300, or 600 s (multiples of spins). All data analyzed in this study are from low-rate modes, recorded at a rate of 1 every 30 s in the sheath. As shown in the following sections, this temporal cadence sufficiently resolves the injection scale and inertial range of turbulence in the Jovian magnetosheath.

We calculate the numerical moments (density, velocity, and temperature) using the Version 2 Level 3 Ion Species 3 data (protons) from JADE-I with geometric factor found in Kim et al. (2020) and the calibration found in Equation A1 of Wilson et al. (2018) (see Section 4.5.3.2 of McComas, Alexander, et al., 2017 or Paschmann & Daly, 1998). We did not remove any background from the L3 V02 data, and we did not perform species remapping.

The ion density and velocity, collected by JADE-I and the magnetic field data during this interval, are shown in Figure 2. Several structures of different sizes can be seen in this turbulent interval. We focus on this interval in this work as it is a rather long interval relative to other JADE magnetosheath samples where continuous, high-resolution data are available. This ensures that a wide range of wavenumber space can be resolved. Further, no clear large-scale inhomogeneity, for example, shock or wave, is present in the sample. Thus, this interval is an ideal candidate for studying turbulence properties.

The relevant plasma parameters are provided in Table 1. The large (>1) ratio of the fluctuating magnetic field to the mean magnetic field (\( B_{rms} / |B| \)) indicates strong turbulence. The plasma beta is relatively large compared to the average beta reported by Ranquist et al. (2019); however, simulations and solar wind observations show no clear variability in the inertial-range slope with plasma beta (e.g., Chen et al., 2014; Franci et al., 2016).

3. Turbulence Spectra

A key method of studying fluctuation power in a turbulent system is to perform spectral analyses of the various fluctuating quantities. This technique has been increasingly used in space physics as a convenient representation of the statistical properties of the system (e.g., Matthaeus & Goldstein, 1982). Spectral slopes can reveal a great deal of information regarding the nature of fluctuations at different scales—from the nature of energy injection or driving, to cascade and kinetic dissipation (Horbury et al., 2008; Parashar et al., 2018).

We first take fast Fourier transforms of each of the three perpendicular components of the velocity field. This step gives the power of fluctuations for each of the separate components as a function of frequency.
Then, we sum the power of these three components to obtain the total power spectra of the velocity fields. For density, there is only one component, so the same procedure is followed except the summing. The power spectral density of the proton density and velocity field, computed for the magnetosheath interval shown in Figure 2, is presented in the two panels of Figure 3. The two spectra have been “smoothed” with a five-point moving centered average at all but the three lowest and highest frequencies.

Using Taylor’s frozen-in hypothesis, the frequency axis can be interpreted as wavenumber axis (Jokipii, 1973; Taylor, 1938). From Table 1, since the flow speed \( V_f \) of the plasma is much greater than the Alfvén speed, we can assume that the structures are essentially “frozen-in” the plasma, and the time series data are really a one-dimensional cut through the system. Therefore, the observed temporal spectra as functions of frequency effectively refer to spatial variations at wavenumber \( k = 2\pi / V_f \).

Both spectra in Figure 3 display nearly power-law behavior for more than one decade in frequency space between \( f \approx 1 \times 10^{-4} \) and \( 3 \times 10^{-3} \) Hz. Using a least-square straight-line fitting in log–log space for this range, the spectral index for the density spectrum is \(-1.78 \pm 0.05\), and that for the velocity spectrum is \(-1.7 \pm 0.1\). Evidently, both spectral slopes are consistent with Kolmogorov scaling of \( \sim k^{-5/3} \) in this wavenumber range to within errors, strongly indicating the inertial range of scales.

The \(-5/3\) inertial-range wave number density fluctuation spectrum along with the \(-5/3\) kinetic energy spectrum are consistent within the framework of nearly incompressible magnetohydrodynamics (Montgomery et al., 1987). The Kolmogorov scaling of the kinetic energy spectrum, in the inertial range of scales, is characteristic of fully developed turbulence (Kolmogorov, 1941) and indicates the presence of a scale-invariant energy cascade through the inertial range of scales (Verma et al., 1995). This energy, once dissipated at small scales, may contribute significantly to the heating of the Jovian magnetosheath (Saur, 2004; Saur et al., 2002).

Note that the wavenumbers corresponding to the characteristic ion kinetic scales, such as the ion gyro radius \((k\rho_i = 1)\) or the ion inertial range \((kd_i = 1)\), are not resolved in the low-rate science JADE data used here (see Table 1). Therefore, the steepening of the spectrum, usually observed in the kinetic range (Chen et al., 2012; Leamon et al., 1998; Safrankova et al., 2013), cannot be assessed here.

### Table 1

| \( \left\langle V_A \right\rangle \) (km/s) | \( \left\langle B_{\text{rms}} \right\rangle \left\langle |B| \right\rangle \) (cm⁻³) | \( d_i \) (km) | \( \rho_i \) (km) | \( \left\langle V_f \right\rangle \) (km/s) | \( \beta_i \) |
|---------------------------------|-----------------------------------|----------------|----------------|-------------------------------|-------------|
| 15.1                            | 3.6                               | 2.1            | 156            | 1,094                         | 391         |

Note. Data obtained on February 20, 2017. The magnetic-field rms fluctuation amplitude is calculated as \( B_{\text{rms}} = \left\langle |B(t)| - \left\langle |B| \right\rangle \right\rangle \). Alfvén speed, ion density, ion inertial length \( d_i \), Larmor radius \( \rho_i \), plasma flow speed, and ion plasma beta \( \beta_i = v_{\text{th}}^2 / V_A^2 \) are also reported.
The slight flattening of the density spectrum near the end of the inertial range \((f \geq 10^{-2} \text{ Hz})\) is expected from previous observations in the solar wind and Earth’s magnetosheath. However, such flattening of spectrum can also be due to instrumental noise; for example, due to counting statistics (Gershman et al., 2018). So, we do not rule out the additional possibility of instrumental noise also contributing here and refrain from drawing any conclusion in this regard. Similarly, the two peaks seen at the high frequency range of the velocity spectrum are also not physical. Potential cases of beating pattern due to unviewed look directions in 30 s species data may be responsible. The ISSUES flag marks these potential cases. Similar spin tones systematically appear in other charged particle instrumentation (Gershman et al., 2019) while converting measured counts to phase space density. Full investigation of these effects in JADE-I is beyond the scope of this paper and is left for future examination. However, these issues do not affect the results of this study.

At the low wavenumber end of the spectrum, near the wave number \(k \approx 10^{-6} \text{ km}^{-1}\), the “break” in the power-law behavior signifies that uncorrelated fluctuations are being sampled, consistent with calculation of the correlation length, \(L_c \approx 5 \times 10^5 \text{ km} \approx 7 R_J\). We estimate the correlation length as the value of lag \(l\), where the correlation function \(R(l)\) reaches the value of \(R(0)/e\). The correlation function is defined as \(R(l) = \langle v(x) v(x+l) \rangle\). Figure 4 shows correlation function and the exponential fit.

The very low wavenumber part of the spectra, where energy is injected, also generally exhibits power law scaling in turbulent systems (Dmitruk & Matthaeus, 2007; Verdini et al., 2012). The spectral index in this injection range is usually shallower than the Kolmogorov value \(-5/3\) and varies from \(-1\) (fairly common in the solar wind; e.g., Matthaeus & Goldstein, 1986) to positive values (seen in planetary [e.g., Huang et al., 2017] and cometary environment [e.g., Ruhunusiri et al., 2020]). The injection-range spectral slope reveals the nature of energy injection in the turbulent medium. Longer continuous intervals will be required to address these issues for the Jovian magnetosphere. Here, we have focused on the MHD-scales; however, future studies could reveal new physical insights into the large scales.

4. Discussion

Turbulence in the solar wind has been extensively studied with the help of a large fleet of spacecraft (see reviews by Bruno & Carbone, 2005, 2013). Turbulence in the extraterrestrial magnetospheres is relatively less explored. Using the JADE ion data from the Juno Mission, we have presented the spectral properties of the MHD-scale fluctuations in the magnetosheath of Jupiter. We found an approximate \(-5/3\) Kolmogorov scaling as a signature of the presence of classical turbulence cascade.

Historically, solar wind magnetic-field spectra show nearly \(-5/3\) index (the Kolmogorov value); the velocity spectrum in the solar wind typically exhibits \(-3/2\) rather than \(-5/3\) slope (Podesta et al., 2006; Safarkova et al., 2016); and observed that density spectra are typically steeper in the beginning of the MHD range and exhibit a flattening at higher frequencies (e.g., Safarkova et al., 2015 and references therein). We find close to \(-5/3\) index in both velocity and density spectra. These results are
indicative of the difference in the nature of solar wind and magnetosheath plasma. Recent observations in planetary magnetosheaths have shown that turbulence in these regions do not always show a Kolmogorov scaling. For example, the Cassini magnetic-field spectrum in Saturn's magnetosheath, near the nose of the bow-shock, show a transition directly from the injection scales \( \sim f^{-1} \) to the ion kinetic scales \( \sim f^{-4/3} \), without forming the Kolmogorov inertial range \( \sim f^{-5/3} \); however, farther downstream the sheath, in the flanks region, some trend of steepening is observed (Hadid et al., 2015). In the much smaller magnetosheath of Earth, although the Kolmogorov \( -5/3 \) slope is observed rarely, similar steepening toward the flanks is observed (Huang et al., 2017). A possible explanation is that the turbulence is still in the early stage of development after crossing the bow shock in these systems, and therefore, the inertial range is not formed until farther downstream in the sheath. The distance of the Juno spacecraft from the bow shock nose is \( \sim 135 R_J \) (see Figure 1) here. Assuming a uniform flow speed of \( \sim 300 \text{ km/s} \), the flow we are measuring has been in the sheath for \( T_R \sim 300 \text{ km/s} \). The correlation time or “eddy turn-over time” is \( T_c \sim L_c/\nu \) (see Figure 4).

Using a very conservative assumption that this eddy turn-over time has been constant along the plasma's trajectory in the sheath, we estimate that the number of correlation time that the plasma has developed through is \( T_c/T_R \approx 4 \). Therefore, the turbulence plasma has had time to develop for several correlation times, which supports the existence of an extended inertial range. On the other hand, the turbulence in coronal mass ejection (CME)-driven sheaths differ significantly from the planetary magnetosheath (e.g., Kilpua et al., 2020, 2021). The inertial-range spectral indices in the CME sheaths are usually steeper than the Kolmogorov \( -5/3 \) index, with no significant differences between the slopes in the near-shock and near ejecta-leading edge regions. Thus, unlike planetary bow shocks, the interplanetary shocks do not appear to reset the solar wind turbulence.

In the present study, we found that Jupiter’s magnetosheath exhibits spectral behavior consistent with Kolmogorov scaling; whether this behavior is typical of the Jovian magnetosheath, is not possible to conclude with the specific case study presented here. Generation of the Kolmogorov turbulence closer to the magnetopause could also be due to some local instabilities like the Kelvin-Helmholtz instability that develop at the flank of the magnetopause. Further analysis of more intervals is required to derive a more statistically relevant picture and understand the evolution of the turbulence processes in Jupiter’s magnetosheath.

The evaluated correlation length \( \sim 7 R_J \) is much larger than the characteristic ion scale (say, \( \rho_i \approx 1,000 \text{ km} \)) here, resulting in an effective Reynolds number (Bandyopadhyay, Matthaeus, Chasapis, et al., 2020; Bandyopadhyay, Matthaeus, Parashar, Chhiber, et al., 2020; Bandyopadhyay, Matthaeus, Parashar, Yang, et al., 2020; Matthaeus et al., 2005) of \( Re \sim \left( L_c / \rho_i \right)^{4/3} \approx 3500 \). Large Reynolds numbers \((>>1)\) indicates strong turbulence. The broad separation of scales allows the turbulence cascade to proceed from the scales \( \sim L_c \) to scales \( \sim \rho_i \), where kinetic effects become important. As discussed earlier, the selected sample is in the dawnside magnetosheath, quite far downstream in the flanks region. Close to the bow shock nose the correlation length as well as the effective Reynolds number is expected to become smaller. Future work in the different local time regions, if available, could shed some light on some of the open questions.

Data Availability Statement

The JADE-I ion species data are part of the JNO-J/SW-JAD-3-CALIBRATED-V1.0 data set (ion species data, V02 files) and were obtained from the Planetary Data System (PDS) at https://pds-ppi.igpp.ucla.edu/search/view/?id=pds://PPI/JNO-J_SW-JAD-3-CALIBRATED-V1.0. The MAG data were obtained from the PDS at https://pds-ppi.igpp.ucla.edu/search/view/?id=pds://PPI/JNO-J-3-FGM-CAL-V1.0, data set JNO-J-3-FGM-CAL-V1.0, using the fgm_jno_l3_{date}pc_r1s_v01.sts files.

References


