The Astrophysical Journal Letters, 901:L2 (6pp), 2020 September 20 https://doi.org/10.3847/2041-8213/abb199

Intermittency and *q*-Gaussian Distributions in the Magnetic Field of the Very Local Interstellar Medium (VLISM) Observed by Voyager 1 and Voyager 2

L. F. Burlaga[1], N. F. Ness[2], D. B. Berdichevsky[3,4], L. K. Jian[5], J. Park[2,5], and A. Szabo[5]
[1] Leonard F. Burlaga, Inc., Davidsonville, MD 21035, USA
[2] University of Maryland, Baltimore County, Baltimore, MD 21250, USA
[3] IFIR/UNR-CONICET, Esmeralda y 27 de Febrero, Rosario, Santa Fe, Argentina
[4] TRIDENT, NASA/GSFC, Greenbelt, MD 20771, USA
[5] Heliophysics Science Division, NASA/GSFC, Greenbelt, MD 20771, USA
Received 2020 June 10; revised 2020 July 31; accepted 2020 August 12; published 2020 September 16

Abstract

Voyager 1 (V1) observed q-Gaussian distributions of 1 hr increments of the components the magnetic field $\boldsymbol{B}$ throughout the very local interstellar medium (VLISM) on scales on the order of 1 year, from 2013 through 2019, excluding the disturbed regions near two shocks. The intermittency of the components of B is described by q from the q-Gaussian distributions of 1 hr increments B as well as by the kurtosis K derived from the time series of the increments of $\boldsymbol{B}$. Farther than ~5 au from the heliopause, Voyager 1 observed larger intermittency in the fluctuations of the predominantly transverse component B_N and in the nearly longitudinal component B_T of $\boldsymbol{B}$. The average values of q for the B_N component and transverse B_T component for these data in the VLISM are $q = 1.32 \pm 0.03$ and $q = 1.22 \pm 0.03$, respectively. The corresponding average values of the kurtosis are $K = 7.2$ and $K = 4.9$. Voyager 2 (V2) crossed the heliopause on 2018 November 5. Near the heliopause, in 2019, V2 observed large intermittency in 1 hr increments of the compressive component B_T and smaller intermittency in B_N. The Voyager 2 observations give $q = 1.51 \pm 0.06$ and $q = 1.17 \pm 0.06$ for the B_N and B_T components of B, respectively, as well as $K = 7.2$ and $K = 12.3$, respectively. The intermittency in B_T and B_N, observed by V2 near the heliopause was significantly larger than that observed by V1 when it was near the heliopause.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar magnetic fields (845)

1. Introduction

This Letter shows that the q-Gaussian distributions of increments of the magnetic field B and the corresponding intermittency are general characteristic of the very local interstellar medium (VLISM). Zank (2015) defined the VLISM as "that region of the interstellar medium surrounding the Sun that is modified or mediated by heliospheric processes or material." For general overviews of the interaction between the heliosphere and the interstellar medium, see Holzer (1989), Parker (1963), and Zank (1999, 2015). Significant disturbances in the VLISM (Burlaga & Ness 2016; Burlaga et al. 2015, 2020), near each of the two shocks in the VLISM, are excluded from this study. Thus, we discuss the q-Gaussian distributions related to the intermittency in the relatively undisturbed VLISM, which includes nearly all of the observations of the VLISM through 2019.

The q-Gaussian distribution function has been studied extensively by Tsallis (1988, 2004, 2006) in the context of nonextensive statistical mechanics, where it is derived from an entropy function. This distribution function has applications to many fields of science (Gell-Mann & Tsallis 2004). It plays a key role in the theory of multifractals, which appear in observations of turbulence (Frisch 1995), the heliosphere, the heliosheath, and other nonlinear dynamical systems.

There are a number of papers related to the heliosphere and heliosheath (e. g. Burlaga & Viñas 2004; Burlaga et al. 2007; Burlaga & Ness 2009) that discuss increments of B, δBm, on a wide range of scales that can be described by a constant A times the "q-Gaussian distribution" $R_q = A[1 + (q - 1)\beta(\delta Bm)^2]^{-1/(q-1)}$, which is defined by three constants: A that describes the amplitude of the single peaked function, β that is inversely related to the width of the distribution, and q that has the value $q = 1$ for a Gaussian distribution. The q-Gaussian distribution, like the Gaussian distribution, is symmetric with a Gaussian core, but it has a large power-law tail. The parameter q decreases more slowly with increasing scale than the kurtosis (Burlaga et al. 2006).

"Intermittency" is a general concept related to a signal that is "bursty" or "spiky" on a variety of scales, containing significantly more large values (outliers) that would be associated with a Gaussian distribution (Staicu 2002 and Frisch 1995). Intermittency was observed in the $\boldsymbol{B}$ and velocity fluctuations in the solar wind near 1 au by Burlaga (1991), Sorriso-Valvo et al. (1999). Intermittency of a time series is frequently quantified by the kurtosis K, which can be computed directly from the time series of a scalar function. The kurtosis of a Gaussian distribution is $K = 3$. In general, the kurtosis is a measure of deviations from a Gaussian distribution, as is the parameter q in the q-Gaussian distribution. Intermittency in a time series is recognized by "spikes" and outliers of the observations, which give rise to a tail on the distribution describing the increments. The variation of q and K as a function of scale is qualitatively the same but quantitatively different (Burlaga et al. 2006). As discussed above, q-Gaussian distributions are ubiquitous in the heliosphere and heliosheath, and we shall show that q-Gaussian distributions are observed nearly everywhere in the VLISM as well.

Voyager 1 (V1) entered the (VLISM) when it crossed the heliopause on 2012 August 15 and began measuring the draped interstellar magnetic field. The strength of the magnetic field B is plotted in Figure 1, where disturbed regions following two shocks (sh) and a pressure front (pf) are indicated. The direction of $\boldsymbol{B}$ changed very slowly during this interval (Burlaga et al. 2020). Kolmogorov turbulence (Kolmogorov 1941) was observed in $\boldsymbol{B}$ of the VLISM (Burlaga et al. 2015, 2018), during two relatively undisturbed "quiet" 468 day intervals. A spectral

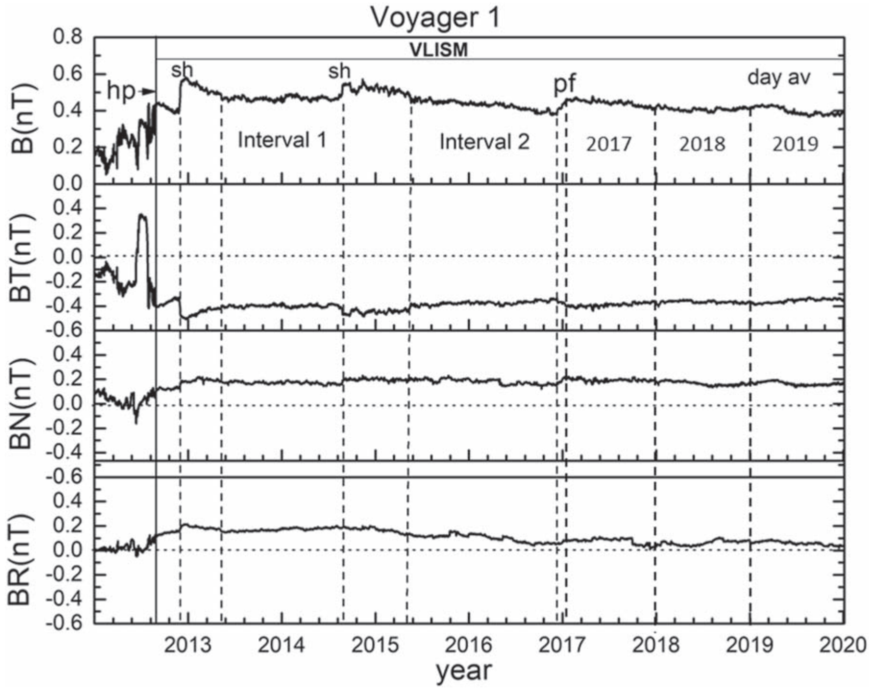

Figure 1. Daily averages of the magnetic field strength B(a) and its components B_R(d), B_T (c), and B_N(e) in the VLISM beyond the heliopause (HP). This Letter discusses intermittency in the observations made between 2013 and 2020, except the disturbed intervals behind the two shocks and just behind the heliopause. Kolmogorov turbulence was observed during Interval 1 and Interval 2. The interval during 2017 behind the pressure front labeled "pf" as well as the observations during 2018 in 2019 were also considered.

analysis of $\boldsymbol{B}$ in the heliosheath and in the VLISM through 2016 by Fraternale et al. (2019) confirmed the existence of Kolmogorov turbulence over a limited frequency range and found evidence of intermittency.

The observation of turbulence in the VLISM is intrinsically difficult, because the fluctuations are small and close to the limits of observation scales of 1 hr and 1 day (of the order 0.02 nT in the V1 data). We shall show that that intermittency (excluding that produced by shocks) and thus possibly turbulence might be present throughout the VLISM from 2013 through 2019, which is the first major objective of this Letter.

Burlaga et al. (2018, 2020) observed that the nature of the fluctuations was converted from compressible ("magnetosonic fluctuations") in the VLISM between the heliopause and ∼5 au to transverse ("Alfvénic") beyond that distance, which Zank et al. (2019) explained as a mode conversion process. Thus, we might expect that the intermittency observed close to the heliopause might be different than the intermittency observed farther from it. Our second objective is to show that relatively intense intermittency associated with compressive fluctuations as well as smaller transverse fluctuations was observed by V2 in the VLISM close to the heliopause.

Our third objective is to demonstrate that q-Gaussian distributions of the components of $\boldsymbol{B}$ and intermittency in the components exists throughout the VLISM (except in the regions of two shocks, which should be discussed separately) observed by V1 from 2013 through 2019.

2. Measuring Intermittency in the VLISM

There is no unique definition of intermittency (Frisch 1995; Staicu 2002), but for a one-dimensional signal in the solar wind, heliosheath, and VLISM, it is customary to describe intermittency by a function $dX_m(t, \tau_m) \equiv X(t+ \tau_m) - X(t)$ on scales τ_m, where t is the observation time, and X is a component of $\boldsymbol{B}$ or the magnitude of $\boldsymbol{B}$. This Letter analyzes hourly averages of $\boldsymbol{B}$ and uses $\tau_{1h} = 1$ hr.

Our objective is to explicitly demonstrate the existence of intermittency throughout the VLISM (excluding the regions near two shocks) and quantify it. We use V1 observations made during each of five intervals, from 2013 through 2019, ranging from slightly less than 1 year to 468 days, as listed in Table 1, as well as V2 observations during 2019. We work with t corresponding to hourly averages of the magnetic field components. One expects the intermittency to be relatively small at these scales, but we will show that observations of scales of 1 hr suffice to exhibit the existence of intermittency throughout the VLISM observed from 2013 through 2019.

The measurements of $\boldsymbol{B}$ are made in a coordinate system that is fixed in the spacecraft, the spacecraft centered RTN coordinate system. In this system the dimensionless unit vector $\boldsymbol{R}$ is directed radially away from the Sun, $\boldsymbol{T}$ is parallel to the solar equatorial plane and aligned with the direction of the Sun's rotation, and the unit vector $\boldsymbol{N}$ completes the right-handed coordinate system. Thus, $\boldsymbol{B} = B_R\boldsymbol{R} + B_T\boldsymbol{T} + B_N\boldsymbol{N}$. The $\boldsymbol{T}$ direction is ∼30° from the average magnetic field, and $\boldsymbol{N}$ is nearly orthogonal to the average magnetic field throughout the interval considered in this Letter. The V1 spacecraft is not rotating, except for calibrations and special circumstances, and it is oriented such that antenna is directed toward the Earth. Thus, one component of each of the two magnetometers (outboard and inboard) is oriented close to in the $\boldsymbol{R}$ direction at large distances from the Sun.

Table 1
Parameters for q-Gaussian Fits to the Increments of the BN and BT Components of B and Kurtosis (K)

Hr Av	S/C	q–BN	K–BN	q–BT	K–BT	β BN	β BT	Note	Year
Compressive	V2	1.51 ± 0.07	7.2	1.82 ± 0.04	12.3	14,600 ± 900	27,600 ± 600	Near HP	2019
Compressive	V1	1.04 ± 0.12	3.6	1.12 ± 0.05	5.0	39,400 ± 4000	21,900 ± 1000	Near HP	2012
Transitional	V1	0.99 ± 0.07	3.1	1.14 ± 0.05	2.8	25,200 ± 1400	25,900 ± 1000	Interval 1	2013–2014
Transverse	V1	1.30 ± 0.02	8.4	1.20 ± 0.04	4.9	35,300 ± 700	25,000 ± 800	Interval 2	2015–2016
Transverse	V1	1.18 ± 0.01	9.2	1.13 ± 0.02	5.7	29,300 ± 400	27,600 ± 500	Front	2017
Transverse	V1	1.38 ± 0.04	5.2	1.26 ± 0.04	4.0	27,100 ± 900	21,100 ± 1000	Quiet	2018
Transverse	V1	1.40 ± 0.05	5.3	1.30 ± 0.02	4.9	23,100 ± 1200	18,100 ± 400	Quiet	2019
Ave. trans.		1.32 ± .03	7.0	1.22 ± 0.03	4.9	28,700 ± 800	22,900 ± 800		

There is inherent noise in the three sensors on each of the two magnetometers on each of the two spacecraft, which was determined to be 0.006 nT in the laboratory, as described by Behannon et al. (1977). He also discussed "drifts" in the signals from each of the sensors in the magnetometers that are nonlinear, sometimes nearly discontinuous, and can be 0.2 nT yr^{-1}. In the VLISM the magnetometers were, until recently, calibrated by rolling the spacecraft through 360° from 1 to 10 times every few months or longer. The spacecraft rotates only about one direction, which is very close to the $\boldsymbol{R}$ direction, so that only the B_{T} and B_{N} components can be calibrated accurately by rotating the spacecraft. It has become necessary to reduce the number of rolls from 10 to 1 or 2, and to do so less frequently because of the decline in power. Nevertheless, it is still possible to calibrate the B_{T} and B_{N} components with an uncertainty of approximately ± 0.02 nT for V1 and ± 0.03 nT for V2 using the methods developed by Berdichevsky (2009). For the present study, we consider only the B_{T} and B_{N} components of $\boldsymbol{B}$, since there is essentially no direct calibration of the relatively small B_{R} component. For the purpose of exhibiting the intermittency throughout the quiet VLISM, it is sufficient to consider only increments of 1 hr.

3. Overview of the Magnetic Field Observations in the VLISM

In this section, we briefly discuss an overview of daily averages of the magnetic field strength B and its components (B_{R}, B_{T}, B_{N}) in the VLISM in the interval from shortly after V1 crossed the heliopause (on 2012 August 25 at a distance of 121.58 au from the Sun and entered the VLISM) to the end of 2019, which is the extent of the available calibrated observations at the time of this writing.

Figure 1 shows that the temporal variations of the daily averages of $\boldsymbol{B}$ are very small, compared to the variations of $\boldsymbol{B}$ observed in the solar wind and heliosheath. We ignore observations in the VLISM close to the heliopause, and we do not consider the first and second shocks (labeled "sh" and denoted by a dashed vertical lines) and the corresponding post-shock flows, in order to avoid the intermittency associated with shocks and the heliopause, which include features different from the intermittency characteristic of the quiet VLISM.

We will consider the observations of B, B_{R}, B_{T}, and B_{N} from 2013.3593 to the end of 2019, which we divided into five intervals that are shown in Figure 1. Two 468 day intervals in Figure 1, Interval 1 and Interval 2, were studied by Burlaga et al. (2015, 2018), who demonstrated the existence of Kolmogorov turbulence in these intervals, which might be associated with intermittency. At the beginning of the third interval, an abrupt increase of the B can be seen just before 2017, as indicated by a vertical dashed line. Since the jump is too thick to be a shock, it has been identified as a pressure front (labeled "pf" in Figure 1) by Burlaga et al. (2019). We exclude this jump, but examine $\boldsymbol{B}$ following the jump continuing to the end of 2017, which happens to include some noteworthy small-scale structures that might also contribute to intermittency. The remaining observations of $\boldsymbol{B}$ that we consider were made during each of the years 2017, 2018, and 2019.

4. Voyager 1 Measurements of Intermittency in the VLISM

As will become apparent below, we are working very close to the limits of the instrument. The uncertainties in the individual components of $\boldsymbol{B}$ are smaller than the uncertainty in the magnetic field strength B, which is derived from all of the components. We do not consider the B_{R} component, because this component cannot be equally accurately calibrated. Thus, we shall examine intermittency in only the B_{N} and B_{T} components as a function of time.

The fluctuations of $\boldsymbol{B}$ close to the heliopause are primarily *longitudinal* (compressible) fluctuations that might be produced by disturbances originating in the heliosheath (Burlaga et al. 2014). However, Burlaga et al. (2015, 2020) have shown that the fluctuations are primarily *transverse* more than ~5 au beyond the heliopause and extending at least as far as 146 au at V1. One might expect that the intermittent fluctuations in the transverse component B_{N} are larger than those in the longitudinal component B_{T} beyond ~5 au.

We begin by studying the intermittency in the time series of hourly averages of $\boldsymbol{B}$. The procedures for identifying and quantifying relatively weak intermittency in the VLISM will be illustrated for the observations in Interval 2 of Figure 1, which has been shown to be associated with Kolmogorov turbulence (Burlaga et al. 2018). First, we compute 1 hr increments of the fluctuations $\delta B_{\mathrm{N}}1(t,\ \tau_{1h}) \equiv B_{\mathrm{N}}1(t+\tau_{1h}) - B_{\mathrm{N}}1(t)$ and $\delta B_{\mathrm{T}}1(t,\ \tau_{1h}) \equiv B_{\mathrm{T}}1(t+\tau_{1h}) - B_{\mathrm{T}}\ 1(t)$, where τ_{1h} is an hour interval for each hour of the data in Interval 2. Plots computed from the histograms of the increments $\delta B_{\mathrm{N}}1(t,\ \tau_{1h})$ and $\delta B_{\mathrm{T}}1(t,\ \tau_{1h})$ for each hour during the Interval 2 are shown in the left and right panels of Figure 2, respectively, where they are designated $\delta B_{\mathrm{N}}1$ and $\delta B_{\mathrm{T}}1$. The heights of the bars of the histograms of these quantities are plotted as points in Figures 2(a) and (c).

The distributions of hourly increments of $\delta B_{\mathrm{N}}1$ and $\delta B_{\mathrm{T}}1$ observed during Interval 2 are shown by the distribution functions in Figures 2(a) and (c), respectively, which were

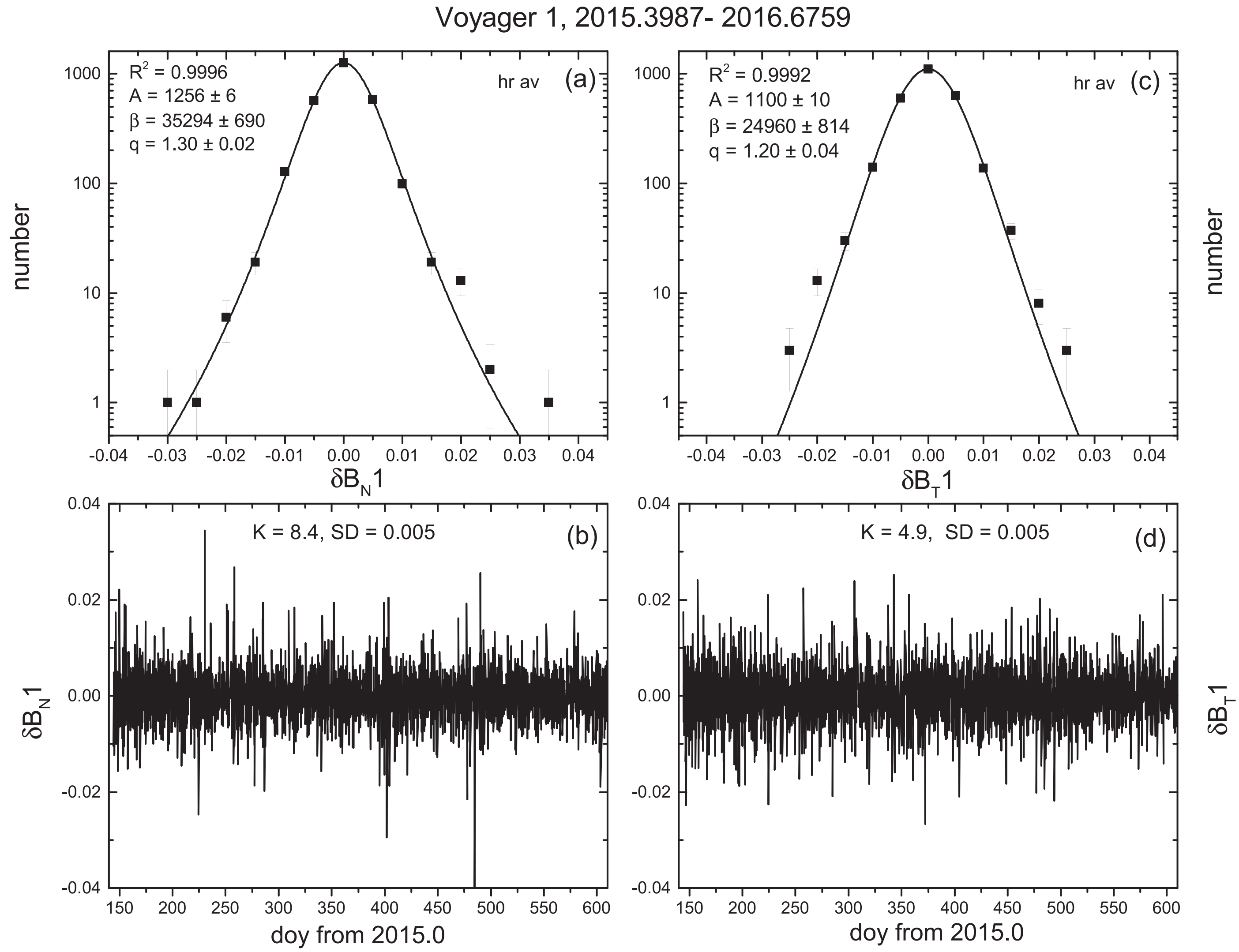

Figure 2. Observations of intermittency using hourly average data by Voyager 1 from 2013.3593 to 2014.6373. Panel (b) shows the time series of 1 hr increments in the B_N component of the magnetic field, labeled $\delta B_N 1$, as a function of time. (a) The points derived from a histogram of the success of 1 hr increments in the component B_N of the magnetic field $\boldsymbol{B}$ ($\delta B_N 1$). The solid curve is a fit of a q-Gaussian distribution to the observations. The value of q, a measure of the intermittency of the fluctuations, is shown in the upper right corner of the panel together with the amplitude A and the parameter β that is inversely related to the width of the distribution. R^2 is the coefficient of determination of the fit. The panels on the right, (c) and (d), correspond to the panels on the left except that they refer to the 1 hr increments in the B_T component of the magnetic field, $\delta B_T 1$.

fitted with the q-Gaussian distributions that are shown by the smooth curves passing through each of the points derived from the observations. The coefficients of determination $R^2 = 0.9996$ and 0.9992 for $\delta B_N 1$ and $\delta B_T 1(t, \tau_1)$, respectively, indicate excellent fits to the distributions of the observations of the points in Figures 2(a) and (c), respectively. The values of q are 1.30 ± 0.02 and 1.20 ± 0.04 for the hourly increments of $\delta B_N 1$ and $\delta B_T 1$, respectively. The small uncertainties indicate the observed q values are well outside the value $q = 1$ for a Gaussian distribution, and they show that intermittency was observed in the fluctuations of $\delta B_N 1(t, \tau_{1h})$ and $\delta B_T 1(t, \tau_{1h})$.

The intermittency q derived from the q-distributions for all of the data in the five intervals discussed in Section 3 are presented in Table 1. Note that value of q for the hourly averages in Interval 1, for which Kolmogorov turbulence was observed by Burlaga et al., was only $q = 0.99 \pm 0.07$ for the transverse ("Alfvénic") component of fluctuations $\delta B_N 1$, which is consistent with a Gaussian distribution, with no intermittency. For the corresponding compressible fluctuations in $\delta B_T 1$, $q = 1.14 \pm 0.05$, which is small but statistically significant. Since Interval 1 is within $\sim$5 au of the heliopause, the fluctuations are compressible, possibly because they originated in the heliosheath, as suggested by Burlaga et al. (2014) and calculated by Zank et al. (2017).

The average values of q for the remaining four intervals in Figure 1 are 1.32 ± 0.03 for $\delta B_N 1$ and 1.22 ± 0.03 for $\delta B_T 1$, which indicates significant departures from a Gaussian distribution, demonstrates the presence of intermittency of these fluctuations, and shows the dominance of transverse fluctuations beyond $\sim$5 au. At these larger distances, the intermittency was primarily in the transverse component, but there was a significant contribution in the longitudinal component as well. A summary of these results and related parameters β and A is given in Table 1.

We conclude that significant intermittency in 1 hr increments of averages of the transverse ("Alfvénic") component B_N and to a lesser extent in the longitudinal component B_T was observed

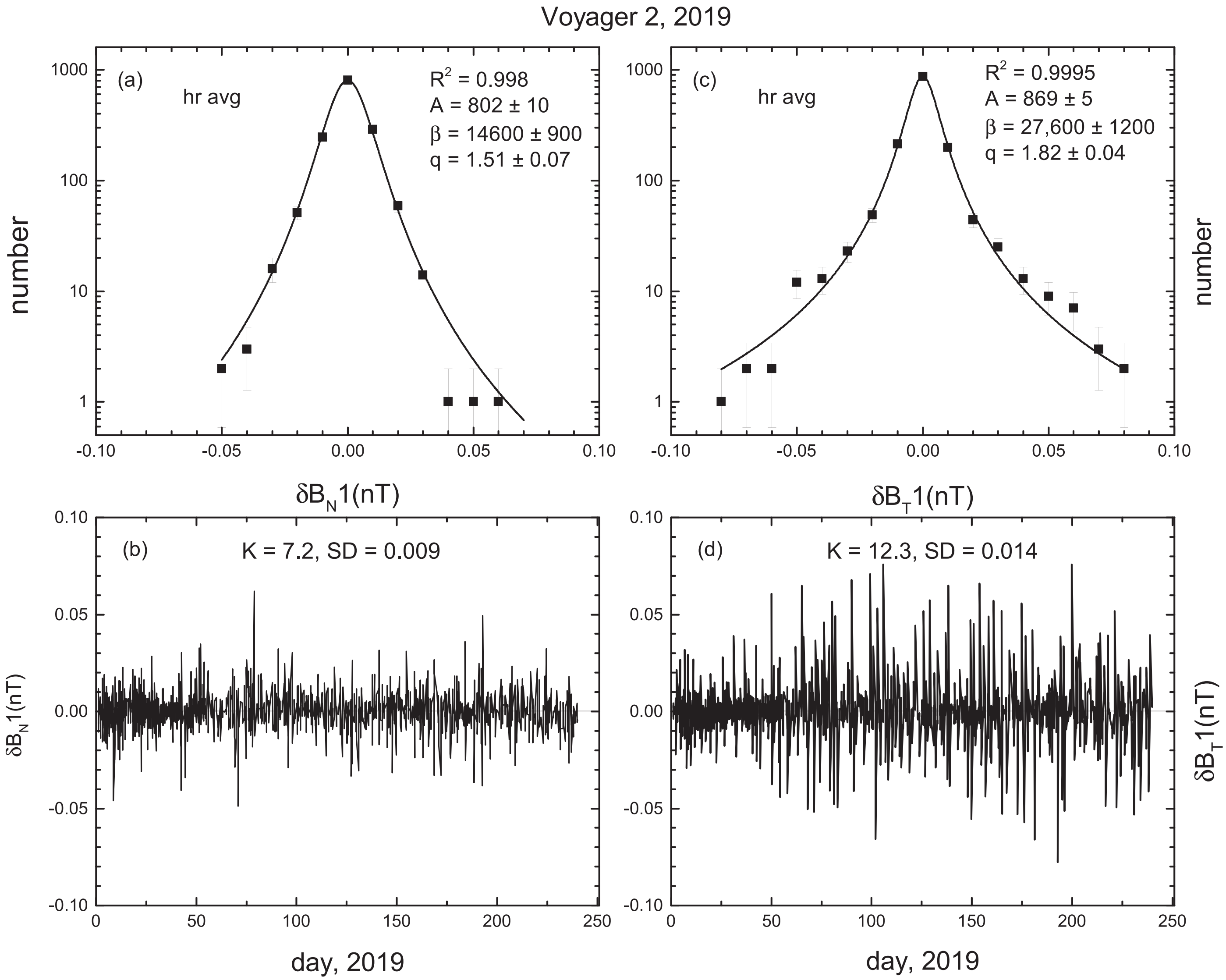

Figure 3. Observations of intermittency for hourly average data from V2 in the VLISM just beyond the heliopause, in 2019. This figure has the same format as Figure 2.

by the V1 magnetic field instrument in the VLISM, except near the heliopause where the compressible component B_T was dominant. For the observations during Interval 1, the intermittency in the transverse component was almost negligible, and it was small but significant in the longitudinal (compressional) component, which might have been associated with compressible fluctuations that originated in the heliosheath.

5. Voyager 2 Measurements of Intermittency in the VLISM

Voyager 2 (V2) crossed the heliopause in the southern hemisphere on 2018 November 5 when it began measuring magnetic fields of the VLISM. Currently, we have data only through 2019, day 240, so we consider only the observations of hourly averages of $\boldsymbol{B}$ during 2019, excluding the observations during November and December of 2018 in order to avoid transient perturbations that might be present near the heliopause.

Proceeding as above, we consider only the B_N (transverse) and B_T (compressible/longitudinal) components of $\boldsymbol{B}$. (One can think of the transverse component as related to Alfvén waves and the compressible component as related to magnetosonic waves.) Plots of the 1 hr increments of the transverse component $\delta B_N 1$ and longitudinal component $\delta B_T 1$ are shown in Figures 3(b) and (d), respectively. Intermittency can be seen in both components, but the intermittency in the compressible component $\delta B_T 1$ is particularly large and notable. From the q-Gaussian fits we obtain $q = 1.51 \pm 0.07$ ($K = 7.2$) for the transverse component $\delta B_N 1$ and $q = 1.82 \pm 0.04$ ($K = 12.3$) for the compressible component $\delta B_T 1$. Clearly, the intermittency in the compressible component was dominant near the heliopause, consistent with the hypothesis of Burlaga et al. (2014), the V1 observations of Burlaga et al. (2018, 2020), and the theory of Zank et al. (2017, 2019).

For the V1 observations made near the heliopause we found that $q = 1.04 \pm 0.12$ ($K = 3.6$) for the transverse component $\delta B_N 1$ and $q = 1.12 \pm 0.05$ ($K = 2.8$) for the compressible component $\delta B_T 1$.

Why were the V2 observations of the intermittency near the heliopause so large and the corresponding V1 observations so small? One possibility is that the heliopause was moving outward when V2 crossed it, creating a disturbance analogous to that produced by a shock. In fact, $\boldsymbol{B}$ decayed exponentially with increasing time beyond the heliopause (Burlaga et al. 2020), as observed behind the two shocks that moved past V1 shown in Figure 1.

6. Summary

We have identified intermittency in the longitudinal and the transverse components of $\boldsymbol{B}$ observed by V1 throughout the quiet VLISM from 2013 through 2019, i.e., everywhere except behind shocks and near the heliopause, where intermittency might be greater. Specifically, we identified intermittency in the 1 hr increment $\delta B_N 1h(t, \tau_{1h})$ of the magnetic field component B_N, which is primarily transverse to the average magnetic field direction, except near the heliopause. We also identified intermittency in the 1 hr increments $\delta B_T 1h(t, \tau_{1h})$ of the magnetic field component B_T near the heliopause that was compressible, since it was primarily along the average magnetic field direction in the quiet VLISM. We conclude that intermittency in $\boldsymbol{B}$ does exist throughout the quiet VLISM.

The intermittency in the VLISM was greater for the predominantly transverse B_N component of $\boldsymbol{B}$ than that of the predominantly longitudinal B_T component, except $< \sim 5$ au from the heliopause where the intermittency was dominant in the compressive B_T component. Thus, the intermittency in the transverse component is dominant in the VLISM beyond several au of the heliopause.

The intermittency was measured by the parameter q in the q-Gaussian fits to the distribution of increments of $\boldsymbol{B}$ components and by the kurtosis. The average values of the intermittency associated with the 1 hr averages of the B_N and B_T components of $\boldsymbol{B}$ during the four intervals beyond $\sim$5 au of the heliopause are $\langle q \rangle = 1.32 \pm 0.03$ for the transverse component B_N and $\langle q \rangle = 1.22 \pm 0.03$ for the longitudinal component B_T of the hourly increments of $\boldsymbol{B}$. The corresponding average values of the kurtosis are 7.0 and 4.9, respectively.

Voyager 2 recently crossed the heliopause and entered a region where compressible fluctuations were dominant and the intermittency was greater in the compressible component than that the transverse component, as might be expected near the heliopause in the VLISM. However, the intermittency in the compressible B_T component was large ($q = 1.82 \pm 0.04$, $K = 12.3$). Even the intermittency in the B_N component ($q = 1.5 \pm 0.07$, $K = 7.2$) observed by V2 was large compared to the corresponding average values observed by V1 between 2013 and 2019. The intermittency in the V1 observations of B_N and B_T near the heliopause was much smaller than that observed by V2 near the heliopause. Specifically, the intermittency observed by V1 in the compressible B_T component was only ($q = 1.12 \pm 0.05$, $K = 5.0$), and the intermittency in the B_N component was ($q = 1.04 \pm 0.12$, $K = 3.6$). The reason for the relatively strong intermittency observed by V2 near the heliopause is not known, although it might be related to the outward motion of the heliopause. The magnetic field strength observed by V2 decayed exponentially with time from a maximum at the heliopause (Burlaga et al. 2020). Such a decay has been observed at each of two shocks that moved past V1, as shown in Figure 1.

J.P. was supported by the Voyager project under a cooperative agreement with the University of Maryland, Baltimore County. L.F.B. was supported by NASA contract 80GSFC19C0012. D.B.B. was supported by the Voyager project under a cooperative agreement support with TRIDENT–BERDICHEVSKY, DANIEL B. We thank OMNIWeb of Space Physics Data Facility (https://omniweb.gsfc.nasa.gov/coho/helios/heli.html) for making the spacecraft orbit data publicly available.

ORCID iDs

L. F. Burlaga https://orcid.org/0000-0002-5569-1553
D. B. Berdichevsky https://orcid.org/0000-001-9357-7973
L. K. Jian https://orcid.org/0000-0002-6849-5527
J. Park https://orcid.org/0000-0002-8989-4631
A. Szabo https://orcid.org/0000-0003-3255-9071

References

Behannon, K. W., Acuña, M. H., Burlaga, L. F., et al. 1977, SSRv, 21, 235
Berdichevsky, D. B. 2009, White Paper, Voyager Mission, Detailed processing of weak magnetic fields I - Constraints to the uncertainties of the calibrated magnetic field signal in the Voyager missions, https://vgrmag.gsfc.nasa.gov/Berdichevsky-VOY_sensor_opu090518.pdf
Burlaga, L., Florinski, V., & Ness, M. F. 2015, ApJL, 804, L31
Burlaga, L. F. 1991, GeoRL, 18, 69
Burlaga, L. F., Florinski, V., & Ness, N. F. 2018, ApJ, 854, 20
Burlaga, L. F., & Ness, N. F. 2009, ApJ, 703, 311
Burlaga, L. F., & Ness, N. F. 2016, ApJ, 829, 134
Burlaga, L. F., Ness, N. F., Berdichevsky, D. B., et al. 2019, NatAs, 3, 1007
Burlaga, L. F., Ness, N. F., Berdichevsky, D. B., et al. 2020, AJ, 160, 40
Burlaga, L. F., Ness, N. F., Florinsky, V., & Heerikhuisen, J. 2014, ApJ, 792, 134
Burlaga, L. F., & Viñas, A. 2004, JGRA, 109, A12107
Burlaga, L. F., Viñas, A., Ness, N. F., & Acuña, M. H. 2006, ApJL, 644, L83
Burlaga, L. F., Viñas, A., & Wang, C. 2007, JGRA, 112, A07206
Burlaga, L. F. 2015, JPhCS, 642, 012003
Fraternale, F., Pogorelov, N. V., Richardson, J. D., & Tordella, D. 2019, ApJ, 872, 40
Frisch, U. 1995, Turbulence: The Legacy of A.N. Kolmogorov (Cambridge: Cambridge Univ. Press)
Gell-Mann, M., & Tsallis, C. (ed.) 2004, Nonextensive Entropy: Interdisciplinary Applications (New York: Oxford Univ. Press)
Holzer, T. E. 1989, ARA&A, 27, 199
Kolmogorov, A. N. 1941, DoSSR, 30, 301
Parker, E. N. 1963, Interplanetary Dynamical Processes (New York: Interscience)
Sorriso-Valvo, L., Carbone, V. V., Consolino, G., & Bruno, R. 1999, GeoRL, 26, 1801
Staicu, A. D. 2002, Intermittency in Turbulence (Eindhoven: Univ. Technology Eindhoven), http://alexandria.tue.nl/extra2/200213784.pdf
Tsallis, C. 1988, JSP, 52, 479
Tsallis, C. 2004, PhyA, 340, 1
Tsallis, C. 2006, PThPS, 162, 1
Zank, G. 2015, ARA&A, 53, 449
Zank, G. P. 1999, SSRv, 89, 413
Zank, G. P., Du, S., & Hunana, P. 2017, ApJ, 842, 114
Zank, G. P., Nakanotani, M., & Webb, G. M. 2019, ApJ, 887, 116