Intermittent turbulence, noisy fluctuations and wavy structures in the Venusian magnetosheath and wake

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Abstract. Recent research has shown that distinct physical regions in the Venusian induced magnetosphere are recognizable from the variations of strength of the magnetic field and its wave/fluctuation activity. In this paper the statistical properties of magnetic fluctuations are investigated in the Venusian magnetosheath and wake regions. The main goal is to identify the characteristic scaling features of fluctuations along Venus Express (VEX) trajectory and to understand the specific circumstances of the occurrence of different types of scalings. For the latter task we also use the results of measurements from the previous missions to Venus. Our main result is that the changing character of physical interactions between the solar wind and the planetary obstacle is leading to different types of spectral scaling in the near-Venusian space. Noisy fluctuations are observed in the magnetosheath, wavy structures near the terminator and in the nightside near-planet wake. Multi-scale turbulence is observed at the magnetosheath boundary layer and near the quasi-parallel bow shock. Magnetosheath boundary layer turbulence is associated with an average magnetic field which is nearly aligned with the Sun-Venus line. Noisy magnetic fluctuations are well described with the Gaussian statistics. Both magnetosheath boundary layer and near shock turbulence statistics exhibit non-Gaussian features and intermittency over small spatio-temporal scales. The occurrence of turbulence near magnetosheath boundaries can be responsible for the local heating of plasma observed by previous missions.
1. Introduction

The structured plasma environment of Venus is a natural plasma laboratory where the planetary ionosphere acts as an obstacle to the supersonic solar wind flow carrying a magnetic field. The absence of an intrinsic magnetic field ensures that this interaction is more comet-like than Earth-like. It is known from the previous missions to Venus (e.g., Russell and Vaisberg, 1983) that the most prominent features include the direct interaction of ionized magnetosheath flow with the ionosphere/quasi-neutral atmosphere, mass loading of the magnetosheath flux-tubes, and the transport/convection of magnetic flux to the wake region, representing also the dominant source for the magnetotail fluxes. However, for most of the time, mainly during time intervals of low solar wind dynamic pressure, the induced and piled up magnetic field around the planetary obstacle represents an effective magnetic barrier, preventing free entrance of solar wind plasma to the Venusian ionosphere (Zhang et al., 2007). The draping of the interplanetary magnetic field (IMF), the accretion of magnetic flux by the planet, the characteristic spatial scales of physical processes as well as the location and specific features of boundaries, all depend on dynamical processes in the solar wind and make this environment unique. The results of Venus Express spacecraft (VEX) provide an altitude for the induced magnetopause of about 300 km at the subsolar point, while the subsolar bow shock distance from the surface of the planet is about 1900 km (Zhang et al., 2007). These values exhibit a solar cycle dependence, i.e. the thickness of the Venusian magnetosheath varies around 1500 km at the subsolar point and widens up to 5000 - 7000 km at the terminator. During time intervals of high solar wind dynamic pressure, the ionopause moves to low altitude (∼ 250 km) and
mainly the ionosphere forms the obstacle responsible for deflecting the solar wind flow. In this case the thickness of the ionopause increases and more direct interaction between the ionosphere and solar wind is possible (Elphic et al., 1981; Russel and Vaisberg, 1983).

In the dayside magnetosheath strong magnetic fluctuations and waves are present (e.g. Luhmann et al., 1983). Mirror mode waves were observed here in case studies (Volwerk et al., 2008a), and also investigated statistically (Volwerk et al., 2008b). On the other hand, the limited spatial scale of the magnetosheath on the dayside might not support a development of a turbulent cascade, the fluctuations rather resemble 1/f noise (f is the frequency). 1/f^α noise is a signature of the presence of independent physical mechanisms driving fluctuations in the magnetosheath (Vörös et al., 2008). Keeping in mind that the ion inertial length is of the order of 100 km, the magnetohydrodynamic (MHD) spatial scales in the Venusian magnetosheath are limited to one or two decades in wave-number space.

The terminator and, further downstream, the night-side region is of particular interest (Spreiter and Stahara, 1992). Here plasma instabilities, vortices, and turbulence can develop near boundaries. For example, Wolff et al. (1980) have shown that the distortion of the ionopause by Kelvin-Helmholtz instability might lead to the formation of magnetic flux ropes inside the ionosphere as well as ionospheric bubbles embedded in the solar wind. Numerical simulations indicate that the Kelvin-Helmholtz instability can occur at the terminator ionopause of Venus (Terada et al., 2002), capable of producing wave structures over 1000 km in size (Amerstorfer et al., 2007; Biernat et al., 2007). In fact, the initial VEX observation detected these wavy structures (Balikhin et al., 2008). A recent study shows that MHD turbulence near and immediately after the terminator is not
fully developed because of the rapid decrease of spectral power toward higher frequencies,
resulting in spectral scaling indices $\alpha > 2$ (Vörös et al., 2008). Further downstream,
in the magnetotail/magnetosheath region, the spectral analysis indicates the presence of
developed inertial range turbulence, with a spectral scaling index $\alpha \sim 1.6$, close to the
values expected for hydrodynamic or magnetohydrodynamic turbulent flows. However,
in the same region, non-gaussian probability density functions (PDF) with typical long
tails, corresponding to intermittent turbulence, were not observed (Vörös et al., 2008).
This can be explained by the shortness of turbulent time series during a tail-crossing, in
particular not allowing a full reconstruction of PDF tails.

The near-Venus tail is highly structured. There is no significant plasma inflow into the
near-Venusian wake. The wake magnetic field is known to be stronger than the IMF and
from the cavity hot plasma is excluded (Bauer et al., 1977). The solar wind-ionosphere
interaction in the presence of the draped interplanetary magnetic field, however, produces
an extended boundary tailward from the terminator, at the inner edge of the magne-
topause, or outer edge of the wake downstream, where boundary layer turbulence can
develop and heat locally the plasma. The width of this boundary layer is limited, does
not include the whole plasma sheet. In order to understand the energy content and en-
ergy dissipation of underlying processes, it is necessary to investigate systematically the
statistical features of fluctuations in the structured near-Venusian plasma environment.
In this paper we statistically analyze the spectral scaling features of fluctuations in the
magnetosheath, wake and near-boundary regions using VEX magnetometer data during
the first twenty days in May 2006. The time resolution of the magnetic data is 1 s. Due
to rapid crossing of different structures, this time resolution is necessary for obtaining
statistically reliable scaling results. The main emphasis is on the analysis of scalings, i.e. on the evaluation of the continuous part of magnetic power spectra. The analysis of waves (when the continuous parts of the spectra are not considered) is equally important, but out of the scope of this paper. In addition to spectral estimations, we will compare the probability distribution functions (PDFs) and evaluate the scale dependency of their shapes, associated with noisy and turbulent fluctuations. This helps to obtain a more reliable differentiation between turbulence and noise, occurring along the VEX trajectory.

The near-polar orbit of VEX with a periapsis altitude of 250-350 km allows for the first time observations at terminator and mid-magnetotail regions (Zhang et al., 2006). These two important regions were not covered by the previous missions, e.g. Pioneer Venus Orbiter (PVO, Russell, 1992).

2. Near-Venus plasma regions with varying spectral scaling properties

It was reported by Vörös et al. (2008) that the value of spectral scaling index $\alpha$, describing the self-similarity of the power spectrum of the magnetic field data in the frequency range 0.03 - 0.5 Hz, exhibits different values in different regions near Venus. The magnetic fluctuations are non-stationary, e.g. in the magnetosheath the magnetic field strength is increasing towards the induced magnetopause, which introduces a trend into magnetic field data. In order to estimate $\alpha$ robustly, we used a wavelet method proposed by Abry et al. (2000) and applied it successfully to the description of magnetic fluctuations in the Earth’s plasma sheet (Vörös et al., 2004). In this paper we use the Daubechies wavelets, for which finite data size effects are minimized and the number of vanishing moments can be changed. The latter feature of Daubechies analyzing wavelets
is essential to cancel the influence of polynomial trends or periodic structures in the data on the estimation of the scaling index.

Let us demonstrate first how the spectral scaling features vary along the VEX trajectory during its journey from the dayside magnetosheath through the terminator region and wake to the post-terminator magnetosheath. As an example, we show the variation of total magnetic field strength $B$ on May 19, 2006 (Figure 1 top) together with the corresponding power spectral densities (PSD) calculated during equally long time intervals ($a$, $b$, $c$, $d$ and $e$, Figure 1, bottom subplots) along the spacecraft trajectory. Zhang et al. (2007) have already demonstrated that a crossing of each physical region in the near-Venus plasma environment is recognizable from the variations of strength and wave/fluctuation activity of the magnetic field. Indeed, $B$ is not disturbed before $t_1 = 0115$ UT and after $t_2 = 0310$ UT, the spacecraft is in the solar wind (Figure 1). The planetary obstacle perturbs the magnetic field only between $t_1$ and $t_2$. During the interval $a$ VEX enters the dayside magnetosheath from the solar wind (VEX trajectories and the intervals $a$-$e$ are shown in Figure 2, left bottom subplot). Here the magnetic field strength is strongly fluctuating and its value increases up to $\sim 50$ nT. The estimated spectral scaling index $\alpha = 1 \pm 0.2$ (the first bottom subplot in Figure 1) is low, indicating that fully developed turbulence is absent in this region (Vörös et al., 2008). Higher values $\alpha = 5/3$ or $3/2$ are expected for hydrodynamic or MHD inertial range turbulence, respectively. After $\sim 0135$ UT $B$ decreases, which corresponds to the closest approach to Venus, VEX is close to or below the induced magnetopause (Zhang et al. 2007). Between 0140 and 0205 UT high frequency fluctuations are absent, only low frequency wavy fluctuations are seen. These wavy structures might be associated with Kelvin-Helmholtz instability at the
terminator ionopause or detached plasma clouds near the terminator, observed already
during Pioneer Venus orbits (Brace et al., 1982). During interval b the corresponding
spectrum exhibits significant wave power only near 0.07 Hz (~ 14 s) then the spectral
power rapidly decreases with a scaling index $\alpha = 2.5 \pm 0.2$ (the second bottom subplot in
Figure 1). Further downstream (after 0205 UT in Figure 1) broad-band fluctuations occur
again. The spectral indices within the intervals c and e are $\alpha = 1.5 \pm 0.2$ and $1.6 \pm 0.2$
respectively, indicating the presence of developed turbulence. In contrary, the interval d,
in between c and e, shows again 1/f noise-like scaling behavior (the last three bottom
subplots in Figure 1).

The physical difference between turbulence and noise is clear. Turbulence in the wake is
a consequence of nonlinear multi-scale interactions and it is strongly dissipative, heating
the background plasma at the small scales. Noisy fluctuations, exhibiting $1/f^\alpha$ scaling
behavior with $\alpha$ around 1, may have multiple physical sources not connected with nonlinear
interactions, typical for turbulence. $0 < \alpha < 1$ over higher frequencies (around 1Hz)
can also be associated with the noise of the magnetometer (Vörös et al., 2004). The low
values of $\alpha$ can also indicate that the spacecraft is not in a physical region where strong
nonlinear interactions and turbulence can exist, e.g., due to low plasma density or lack of
plasma flows. In the following, the notation '1/f noise' refers to $1/f^\alpha$ noise with spectral
scaling index in a range of $\alpha \in (0.6, 1.4)$ (find below the definition of the spectral index
used in this paper).

In this paper we put the emphasis on statistical examination of the circumstances
under which developed turbulence occurs in the post-terminator wake and magnetosheath
regions.
3. Statistical analysis of magnetic fluctuations

We investigated the time series of magnetic field strength statistically, obtained in the near-Venusian space during the first twenty days in May 2006. During one day one orbit is performed, therefore, during the twenty day interval we have observed twenty crossings. Due to the non-homogeneity and dynamical nature of the near-Venus physical regions the occurrence and the length of at least quasi-stationary intervals slightly differs each day. We identified the approximate beginning and end of the steady intervals computing the scaling indices over time scales 2-30 s, using the wavelet method within sliding overlapping windows. After that, changing slightly the starting point and the length of turbulent/noisy data, optimized data intervals with smallest errors in $\alpha$ were found. We rejected time intervals where the error of the estimation of $\alpha$ was larger than $\pm 0.3$. The available steady intervals in the dayside magnetosheath are shorter, so we selected 9 min long intervals there. Further downstream 12 minute long intervals were selected. Selecting longer data periods would significantly reduce the number of available intervals, while shorter data sets would decrease the statistical reliability of results. Data intervals with fluctuating magnetic field shorter than 12 minutes were not included into our analysis. Due to occasional data gaps or shortness of steady fluctuations in the time series, the number of events is not the same in different physical regions. There were crossings with no steady fluctuations along the VEX trajectory. There were also crossings where the time interval with steady fluctuations was longer than 24 minute.

Due to data gaps or shortness of statistically stationary time series, only 17 out of 20 crossings are shown in Figure 2 (left bottom and right subplots). A cylindrical coordinate system is used in Figure 2, where the events are shown in $\sqrt{(Y^2 + Z^2)}$ VSO vs. $X$ VSO.
(bottom left) or in VSO coordinate pairs (right subplots). VSO is the Venus-centered Venus-Sun-Orbital coordinate system, where X is in the direction of the Sun, Y opposite to the orbital direction of Venus and Z perpendicular to the orbital plane, positive to ecliptic north.

The near-Venusian space is physically non-homogeneous and the spatial and temporal variations cannot be straightforwardly separated from single-spacecraft measurements. Nevertheless, during the investigated time period in May 2006, the typical sequence of physical regions visited by VEX remained approximately the same as in Figure 1: crossing of the dayside magnetosheath (increasing $B$, interval a), low-frequency wavy structures after the terminator (interval b) and entering into the region of broad-band fluctuations further downstream (intervals c-e). The intervals a-e were introduced for the event on May 19, 2006 (Figure 1: top and Figure 2: top-left). The wavy structures are not always present along the whole near-terminator region and wake. In the absence of the wavy structures only low amplitude magnetometer noise is observed. Possibly, the occurrence/absence of wavy structures can be associated with the upstream conditions. For example, during times when the solar wind dynamic pressure is high the ionopause moves to low altitudes ($\sim 250$ km), and direct interactions between the ionosphere and the solar wind can occur (plasma-plasma interactions or solar wind electric field - ionospheric currents interactions). When the solar wind dynamic pressure is low the ionospheric width increases (Elphic et al., 1981) and the draped IMF above $\sim 300$ km can stop the solar wind more efficiently. In this paper we investigate only the features of magnetic fluctuations, without considering the changes in the upstream conditions. The open triangles (Figure
2: bottom left) indicate the whole region (marks are only on the lowest trajectory) where
the wavy structures appear during the first 20 days in May 2006.

Due to the similarity of crossings, the depicted intervals (lines) along the trajectories
(Figure 2: bottom-left), in terms of spectral properties, refer generally to similar physical
regions along the VEX trajectory. For example, the thick black lines (Figure 2: bottom-
left) indicate turbulent processes identified through a spectral scaling index near \( \alpha = 1.6 \).

The location of turbulence in space approximately coincides with time intervals c and
e. The time interval d coincides roughly with the position of grey ‘+’ signs along the
trajectory, where scaling indices corresponding to \( 1/f^\alpha \) noise were observed. For a better
visibility, the trajectories together with turbulent and noisy time intervals (c, e and d) are
depicted in the VSO coordinates (Figure 2: right subplots). From Figure 2 (right bottom)
it is visible that the spatial regions exhibiting the same \( \alpha \) along multiple trajectories are
partially overlapping, indicating that these regions and the corresponding boundaries are
moving or the fluctuations are patchy or intermittent. Moving boundaries can appear in
connection with changing conditions in the solar wind.

Switching between temporal and spatial coordinates helps us to identify spatial regions
with typical scalings. Occasionally we will use plural indicating the change between
temporal and spatial coordinates. For example, the notation 'intervals c' means the set
of all crossings in space near the time interval/space region c on 19 May, 2006.

Figure 3 shows histograms with the number of events per unit interval of the scaling
index \( \alpha \), estimated during the time periods a-e. In each subplot, the horizontal lines over
the histograms represent the average of 95% confidence limits for the mean in each value
of \( \alpha \). The largest average uncertainty corresponds to the dayside magnetosheath region,
where the length of analyzed data was shorter. Figure 3 indicates that the specific scaling
features characterize the statistical properties of different regions in space rather well.

During the magnetosheath periods (intervals a and d: top and bottom subplots in Fig-
ure 3) only two events display scaling indices $> 1.3$, for the other events $\alpha \in (0.6 - 1.25)$.
This indicates that the fluctuations or waves present in the magnetosheath, except for a
few cases, usually do not evolve to a fully developed turbulence state. The observed range
of scaling indices suggests that the continuous part of the magnetosheath spectra is associ-
ated with $1/f$ noise rather than turbulence. Noisy fluctuations can be convected from the
dayside magnetosheath (interval a) to the post-terminator magnetosheath downstream
(interval d), where the spectral power is smaller, possibly the driving sources are more
distant than at the dayside (compare the spectra corresponding to the intervals a and d
in Figure 1).

In the post-terminator wake (intervals b in Figure 3) wavy structures dominate with
periods from 5 to 50 s (similar to event b in Figure 1). Since towards higher frequencies
the power rapidly decreases ($\alpha \sim 2.5$) independent driving sources associated with broad-
band noise or nonlinear multi-scale turbulence are absent.

Finally, a well discernible turbulence scaling index $\alpha \sim 1.6$ was observed during the
intervals c and e (Figure 3: third subplot from top). The events from both intervals are
plotted together because the corresponding scaling indices are similar.

The cartoon in Figure 4 helps to interpret the occurrence of typical scaling regimes,
summarizing the results of the statistical analysis along VEX trajectory in the cylindrical
VSO coordinate system: (1) $1/f$ noise appears under rather different conditions in the
magnetosheath: in front of the planetary obstacle and downstream in the post-terminator.
magnetosheath (regions a, d: squares in Figure 4). Scaling indices which can be associated with turbulence occurred in \( \sim 5\% \) of cases (see Figure 3); (2) Coherent wavy fluctuations occur between the dayside magnetopause and post-terminator boundary of the wake (largely within the optical shadow, region b: triangles in Figure 4), where noise and turbulence are absent (only magnetometer noise is present when the wave activity is absent). Closer to the terminator, the wavy structures can be associated with the Kelvin-Helmholtz instability occurring at the terminator ionopause, resulting probably in detached plasma clouds, first observed during the Pioneer Venus mission by Brace et al. (1982). The PVO spacecraft observed filamentary structures (rays), density holes and radially aligned draped magnetic field lines in the near-planet night side wake (Luhmann and Russel, 1983; Marubashi et al., 1985); (3) Developed turbulence is present at or near boundaries: at the wake/magnetopause/magnetosheath boundary and near the bow shock (regions c, e: circles in Figure 4).

4. Discrimination between boundary turbulence and magnetosheath noise

Figure 3 shows that, in terms of spectral scaling characteristics, turbulence and noisy intervals are well separable. In the following we will further investigate some other differences between turbulence (intervals c and e) and noisy magnetosheath fluctuations (intervals d). We first recall some similarities between the observations obtained from previous missions and VEX near the regions with developed turbulence.

Early observations from Mariner 5 (Bridge et al., 1967) already showed the existence of a plasma boundary located at the inner edge of the post-terminator magnetosheath (VEX is crossing this region where the occurrence of turbulence is depicted by the bottom circle in Figure 4). During a flyby, Mariner 5 found the location of the boundary layer from
∼ 3.2 to 4.5 \( R_V \) behind Venus and from ∼ 2 (magnetopause location) to 3.5 \( R_V \) from the center of the wake. Within the boundary layer Mariner 5 observed a strongly fluctuating lower intensity magnetic field, a decrease of the density and velocity, but an increase of the temperature. The magnetic field strength was larger when the spacecraft entered from the inner magnetosheath, across the magnetopause, to the wake. VEX observations show that the magnetopause location is rather variable over distances \( XVSO < -1R_V \) (open circles in Figure 2: left bottom). Therefore, multi-point turbulence fluctuations indicating the crossing of the magnetopause start in different distances from the center of the wake.

For example, on May 19, 2006 (Figure 2: left top) the strongly fluctuating magnetic field strength reaches a local maximum at about 0205 UT, then it slowly decreases. It indicates that VEX is entering to the boundary layer from the wake (from intervals b to c) and at the boundary the character of fluctuations is suddenly changing, from scaling index \( \alpha \sim 2.5 \) to \( \alpha \sim 1.6 \) (see also Figure 1).

Another interesting feature includes the change of the sign of \( B_X \). During the interval c on May 19 it happens several times (Figure 2: top left). It can indicate that VEX is crossing the neutral sheet behind the planet. The VEX trajectory for this day (marked by an arrow in Figure 2, top right subplot) is roughly along \( Y \) \( \sim 0.9R_V \). In fact the Venusian wake/magnetotail can be formed by flux tubes convected around or slipping over the planet and filled with the plasma from the day side. At the same time, both ends of the flux tubes are co-moving with the solar wind. In a simple case, the resulting magnetic field in the tail is stretched along the X axis, because the central part of the flux tubes is slowed down by the planet while both ends travel faster with the solar wind. Since the IMF is usually close to the ecliptic plane, the tail current sheet, in ideal case,
should be formed by the stretched magnetic field mainly in the north-south plane (Russell and Vaisberg, 1983). Depending on the upstream IMF and its draping around the planet, the current sheet plane in the Venusian magnetotail can also rotate (Luhmann et al., 1991). Since turbulence can drive local mixing and vorticity, the change of the magnetic field direction might be also associated with turbulence, not necessarily with neutral sheet crossing. For example, $B_X$ is also changing sign several times during the shock associated turbulence interval $t$ (Figure 2: top right), but it has nothing common with a neutral sheet crossing.

The same magnetic field and plasma signatures of the inner magnetosheath boundary layer were observed by other missions, too. For example, Venera 10 observed the boundary layer tailward from the Mariner 5 flyby (Romanov et al., 1978). The near-terminator part of the boundary layer was investigated during the Pioneer Venus Orbiter mission. Perez-de-Tejada et al. (1991, 1993) have seen the boundary between the bow shock and magnetopause (they are using the term ionopause instead) in the vicinity of and downstream from the terminator. The boundary layer observed in different distances along the inner edge of magnetosheath confirms the persistent presence of this boundary as a rarefaction wave emerging from the terminator magnetopause and extending downstream.

The high level of magnetic fluctuations and occurrence of magnetohydrodynamic waves near a quasi-parallel Venusian bow shock is well-known from the PVO mission (Luhmann et al., 1983). In this paper we emphasize the detection of intermittency near the Venusian bow shock and its differentiation from magnetosheath noisy fluctuations. Also, we investigate only the magnetic field signatures of the boundary layers.
4.1. Magnetic field orientation

First, we investigate the local magnetic conditions under which turbulence (or noise) can appear. For this purpose we calculate the instantaneous contribution of magnetic field VSO components to the total magnetic field:

\[ b_X(t) = \frac{B_X(t)}{B(t)} \]
\[ b_Y(t) = \frac{B_Y(t)}{B(t)} \]
\[ b_Z(t) = \frac{B_Z(t)}{B(t)} \]

and \( b(t) = b_X^2(t) + b_Y^2(t) + b_Z^2(t) = 1 \). Our goal is to compare the average magnetic field direction during turbulent (c, e) and noisy (d) intervals, when the scaling index is well defined (see Figure 2). Since \( \alpha \) is a statistical descriptor over 12 min long intervals the mean values \( \langle b_X^2 \rangle \), \( \langle b_Y^2 \rangle \), and \( \langle b_Z^2 \rangle \), respectively, were computed over the same time periods; their sum is again 1. Each average defines the relative contribution of a magnetic VSO component to the average magnetic strength during the considered intervals.

Figure 5 compares the local mean magnetic field components with the values of scaling indices estimated during the same 12 min long intervals (open and filled circles). The horizontal lines are averages of points over the noisy \( \alpha < 1.4 \) and turbulent \( \alpha = 1.6 \pm 0.2 \) scaling index ranges. These distinct ranges of \( \alpha \) correspond to the statistical results in Figure 3. The filled circles correspond to turbulent intervals within the magnetosheath boundary layer, while, over the same range of \( \alpha \)s, the open circles correspond to bow shock associated turbulent intervals.

The horizontal lines in Figure 5 show that, over the turbulence range, the average of \( \langle b_X^2 \rangle \) and \( \langle b_Z^2 \rangle \) is larger while the average of \( \langle b_Y^2 \rangle \) is smaller than over the noise range of scaling indices. Therefore, when turbulence is observed \( \langle b_X^2 \rangle \) dominates over \( \langle b_Y^2 \rangle \) and the latter is still stronger than the increased \( \langle b_Z^2 \rangle \). Magnetosheath boundary layer associated turbulence intervals (filled circles - intervals c in Figure 2) show
even larger $<b_X^2>$ values than the near-shock turbulence values (open circles - intervals in Figure 2, over the same $\alpha$ range). In accordance with our findings, the analysis of PVO magnetic, electric and plasma data has shown that, near the terminator region but within the magnetosheath boundary layer, the magnetic field is nearly aligned with the Sun-Venus line (X VSO direction). It was interpreted in terms of a friction-like viscous interaction between the shocked solar wind and the ionospheric plasma over the magnetic polar regions where the draped interplanetary magnetic field lines slip over the planet (Perez-de-Tejada et al., 1993). The viscous plasma-plasma interaction and frictional heating can explain the enhanced temperatures inside the magnetosheath boundary layer, observed tailward by Venera 10 (Romanov et al. 1978). An alternative explanation is represented by local turbulent heating of the boundary layer plasma. We note that near the magnetopause, where VEX crosses the turbulent boundary layer, the draped interplanetary magnetic field lines are more stretched having a large X VSO component (Figure 4). Although the number of events is rather limited, the near-shock turbulent regions have smaller X VSO but larger perpendicular Y VSO and Z VSO magnetic components than the magnetosheath boundary layer turbulence (Figure 5).

Finally, noise (open circles - intervals d in Figure 2) is associated with a large $<b_Y^2>$, smaller $<b_X^2>$ and almost negligible $<b_Z^2>$. Since the IMF is mostly in the X-Y plane, the large-scale magnetosheath magnetic field is not affected by the boundaries, but exhibiting only noisy broad-band fluctuations and it has the strongest average components in the X-Y plane.

Let us investigate deeper now the intermittent nature of turbulence. Besides the characteristic scaling exponents ($\alpha \sim 1.6$) and the expected average magnetic field directions,
intermittency represents another key feature of fully developed turbulence. Therefore, the occurrence of intermittency represents a further evidence that we are dealing with a real turbulence, capable of heating the background plasma.

4.2. Turbulent intermittency versus Gaussianly distributed noise

Higher order statistics is needed to fully describe the nature of nonlinear fluctuations. In turbulent, non-homogeneous plasma flows the shape of the probability density functions (PDFs) is scale-dependent and peaked with long tails (e.g. Frisch, 1995). Because of the shortness of time series during one crossing the shapes of non-Gaussian PDFs or their scale dependency cannot be evaluated (Vörös et al., 2008). Instead, we construct PDFs from the 15 magnetic time series (realizations) of turbulence for which spectral scaling near $\alpha \sim 1.6$ was observed (events from both c and e intervals in Figure 2). Splitting the data into magnetosheath boundary layer and near-shock turbulence regions would not change the shape of turbulent PDFs significantly. PDFs corresponding to the noisy magnetosheath (intervals d in Figure 2) will be also reconstructed.

PDFs of two-point differences of magnetic field strength were estimated from $\delta B = B(t + \tau) - B(t)$, for $\tau = 2...30$ s. Figure 6 shows the PDFs for $\tau = 3, 30$ s only. Boundary turbulence associated PDFs are shown on the left, 1/f noise related PDFs on the right hand side. The error bars represent 95% confidence limits for the mean in each point of $\delta B$. The dashed grey points are least-square Gaussian fits to the experimental two-point PDFs. The Gaussian PDF is given by $\frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$, where $\mu$ is the mean and $\sigma^2$ is the variance. For the smaller time scale $\tau = 3$ s the tails of the experimental turbulent PDFs are higher than the Gaussian tails. The departure from the Gaussian indicates that non-homogeneously distributed fluctuations become more probable as the scale decreases due
to turbulent structures and long-range interactions (Leubner and Vörös, 2005). Gradual decorrelation is obtained by enhancing the two-point separation scale and a Gaussian is approached for large enough $\tau$ even in a turbulent field. This is because the typical correlations for turbulent structures are lost if the separation is large, and only Gaussianly distributed noise is observed. For $\tau = 30$ s, the PDF is a Gaussian in Figure 6 left. Noise shows Gaussianly distributed PDFs over both time scales.

Let us further investigate the shape of PDFs in terms of statistical moments. Using standard procedures (Press et al., 1992), the skewness ($S$) or the third moment,

$$S(\tau) = \frac{1}{N} \sum_{j=1}^{N} \left( \frac{x_j - \bar{x}}{\sigma} \right)^3$$

(1)

and the kurtosis ($K$) or the fourth moment,

$$K(\tau) = \frac{1}{N} \sum_{j=1}^{N} \left( \frac{x_j - \bar{x}}{\sigma} \right)^4 - 3$$

(2)

are computed for turbulent and noisy intervals, as above. Here $x_j = \delta B(t_j, \tau)$, $\sigma$ is the standard deviation, $\bar{x}$ is the mean value of the elements and $N$ is the number of the data points. In this way the dimensionless $S(\tau)$ and $K(\tau)$ characterize the scale and time evolution of the shape of a distribution ($S$ - asymmetry around the mean; $K$ - peakedness or flatness; both relative to a Gaussian distribution, for which $S = K = 0$). $K$ increases towards small scales in intermittent turbulence (Frisch, 1995).

Figure 7 shows the time-scale ($\tau$) evolution of kurtosis $K(\tau)$ (top) and skewness $S(\tau)$ (bottom) for turbulent (left) and noisy (right) intervals. The error bars represent 95% confidence limits for the mean in each value of $\tau$. As is expected from turbulent PDFs in Figure 6, $K$ is increasing as $\tau$ decreases, which proves that the underlying magnetic
fluctuations are non-Gaussian, peaked and intermittent. $K$ practically does not depend on $\tau$ in the case of 1/f noise, indicating a Gaussianly distributed process.

The skewness remains close to zero (Figure 7: bottom) in both cases, showing symmetric distributions around the mean value.

5. Discussion and conclusions

In this paper the unique data from the VEX spacecraft were used to investigate magnetic fluctuation statistics from Venusian magnetosheath and wake regions. The interaction of the solar wind with the planet drives magnetic fluctuations exhibiting different scaling regimes in different regions of near-Venusian space. To identify spectral scaling ranges and indices, we used a wavelet technique, successfully applied for studying the continuous spectra in the Earth’s plasma sheet turbulence (Vörös et al., 2004). The technique and the data intervals were not optimized for finding waves (peaks in power spectra).

Three types of scaling were observed. Inside the dayside/tailward magnetosheath, far from boundaries, 1/f noise is present in the prevailing majority of cases indicating the contribution of multiple independent driving sources. It also means, that this type of spectral scaling is not formed by an isolated single physical process. In other words, there might exist multiple sources of fluctuations, but no one of them is close enough in space to dominate in the spectral power. This changes when VEX enters to a region where multiple sources are missing, or where a single physical process dominates with a scaling feature other than that of the noise. In fact, these are distinct regions of near-Venusian space where the ‘solar wind - planetary obstacle’ interactions are enhanced or the multiple sources of noise are shielded.
The interaction is enhanced at the terminator ionopause, probably due to the Kelvin-Helmholtz instability, at the magnetosheath boundary layer due to the magnetosheath boundary shear flows and near the quasi-parallel bow-shock. The near-planet wake represents a region which is shielded from the plasma of solar wind origin. Filamentary structures, detached plasma clouds, depleted density holes and radially aligned draped magnetic field lines were observed by PVO spacecraft in the near-planet night side wake (Luhmann and Russel, 1983; Marubashi et al., 1985). The magnetosheath flow is expected to converge into the wake only near $5R_V$ behind the planet (Intriligator et al., 1979). The observed wavy structures near the terminator and in the night side near-planet wake can be associated with the detached coherent structures or holes. The occurrence/absence of these structures can be controlled by the direct interaction between the solar wind and ionosphere, e.g. by the high/low solar wind dynamic pressure. In our interpretation, the spectral index $\alpha \sim 2.5$ indicates, that the coherent wavy structures represent the dominating physical process in this region. Because of the shielding of the near planet wake, turbulence or noise are absent in this region. Due to the converging flows the shielding can disappear at distances close to or larger than $X_{VSO} \sim 5R_V$, where the character of fluctuations would change.

The magnetosheath regions with distinct scaling indices (turbulence or noise) partially overlap (see Figure 2). This can be explained through a movement of boundaries under the influence of changing upstream IMF conditions. Spatial intermittency, typical for turbulence with scale-dependent non-Gaussian distributions, can lead also to interwoven scaling structures. The turbulent regions are formed near the 'supersonic solar wind flow - planetary obstacle' boundaries in the presence of draped IMF. The outer boundary is
the bow shock, where the solar wind slows down and heated for the first time. Here, the
local turbulence is associated with the quasi-parallel shock geometry. Second time the
solar wind flow decelerates at the inner magnetosheath producing a velocity shear near
the magnetosheath boundary layer. The near-terminator ionosphere/magnetopause and
its interaction with the solar wind plays an important role. The rarefaction wave (the
boundary) and the observed plasma conditions in the tailward boundary layer can emerge
from the magnetopause near the terminator and extend downstream (Perez-de-Tejada et
al., 1991). Local heating of the plasma within the boundary layers is also possible through
the shear flow associated turbulence. The spatial size of boundary layer turbulence (see
Figure 2) is roughly between 0.5 and 1 $R_V$, shorter turbulent intervals were observed
near the quasi-parallel bow shock. The width of the noisy magnetosheath in between
the turbulent boundaries is of the same order. The estimation of the spatial sizes of
these regions is rather rough. The data are available only from single point measurements
(the boundaries can move during the measurements) and the 12 min long data intervals
represent a pure resolution. The estimation of scaling indices within shorter time intervals,
however, was not possible due to the large statistical errors in these cases. Multi-point
Cluster observations show, that turbulence downstream of the quasi-parallel terrestrial
bow shock is intermittent and that the level of intermittency increases over the spacecraft
separation, reaching larger values than 8000 km (Yordanova et al., 2008). Our results
show, that the spatial scale of intermittent turbulence is less than 1 $R_V$ near the Venusian
bow shock. In between the near shock region and the magnetosheath boundary layer
fluctuations are noisy (in Figure 4, squares between triangles).
It was shown by Perez-de-Tejada et al. (1993) that the magnetic field is nearly aligned with the Sun-Venus line (X VSO direction) within the near-terminator magnetosheath boundary layer. We found a similar alignment within the boundary layer at a distance of $X \text{VSO} \sim -2.2R_V$ (Figures 2, 5). It indicates, that the magnetic field geometry detected during the viscous plasma-plasma interactions near the terminator ionosphere is conserved and observed further downstream along the VEX trajectory, where the draped magnetic field is stretched (Figure 4).

Data intervals that were found to be turbulent or noisy in the spectral analysis were further investigated using the two-point (time delayed) probability density functions (PDFs). Over large two-point separations (e.g. $\tau = 30\text{s}$), both turbulent and noisy PDFs are well fitted by the Gaussian distributions, indicating the occurrence of uncorrelated fluctuations. Over small separations (e.g. $\tau = 3\text{s}$), large deviations from the Gaussian distribution are observed only for turbulent intervals, noise remains Gaussianly distributed (Figure 6). The scale-dependency of kurtosis (Figure 7) shows that turbulent structures are intermittently distributed, noise is more homogeneous. Skewness remains close to zero in both cases which corresponds to symmetrical distributions. A simultaneous increase of $S$ and $K$ towards small scales would indicate that the multi-scale fluctuations in turbulence might be affected by strong large-scale gradients or close boundaries (Vörös et al., 2007). Therefore, $S(\tau) \sim 0$ for $\tau \in (2 - 30)\text{s}$ is a signature of intermittency, not affected by boundaries along the VEX trajectory over the scale of seconds. However, asymmetries or nonzero skewness in magnetic field statistics can appear below the 1 s time scale. Anyhow, besides the expected spectral index ($\alpha \sim 1.6$), the observation of intermittency represents a further evidence for the occurrence of real turbulence in the near-Venusian space. The
key feature of turbulence is its strong dissipative nature and a capability for the local heating of plasma. Multi-scale turbulence can channel the large-scale energy of the flow to kinetic scales, where dissipation processes are strong. We will investigate this point in a different paper.

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References

Abry, P., P. Flandrin, M. S. Taqqu, and D. Veitch (2000), Wavelets for the analysis, estimation and synthesis of scaling data, in Self-Similar Network Traffic and Performance Evaluation, edited by K. Park and W. Willinger, p. 39, Wiley-Interscience.

Amerstorfer, U.V., N.V. Erkaev, D. Langmayr, and H.K. Biernat (2007), On Kelvin-Helmholtz instability due to the solar wind interaction with unmagnetized planets, *Planet. Space Sci.*, 55, 1811–1816, doi:10.1016/j.pss.2007.01.015.

Balikhin, M.A., S. A. Pope, T. L. Zhang, A.O. Fedorov, M. Gedalin, and S. Barabash (2008), Giant Vortices Lead to Ion Escape From Venus, submitted to *Geophys. Res. Lett.*.

Bauer, S.J., L.H. Brace, D.M. Hunten, D.S. Intriligator, W.C. Knudsen, A.F. Nagy, C.T. Russell, F.L. Scarf, and J. H. Wolfe (1977), The Venus ionosphere and solar wind interaction, *Space Sci. Rev.*, 20, 413–430.

Biernat, H.K., N.V. Erkaev, U.V. Amerstorfer, T. Penz, and H.I.M. Lichtenegger (2007), Solar wind flow past Venus and its implications for the occurrence of the Kelvin-Helmholtz instability, *Planet. Space Sci.*, 55, 1793–1803, doi:10.1016/j.pss.2007.01.015.
Brace, L. H., R.F. Theis, and W.R. Hoegy (1982), Plasma clouds above the ionopause of Venus and their implications, *Planet. Space Sci.*, 30, 29-37.

Bridge, H.S., A.J. Lazarus, C.W. Snyder, E.J. Smith, L. Jr. Davis, P.J.Jr. Coleman, and D.E. Jones (1967), Mariner V: Plasma and magnetic fields observed near Venus, *Science*, 158, 1669–1673.

Elphic, R.C., C.T. Russel, J.G. Luhmann, F.L. Scarf, and L.H. Brace (1981), The Venus ionopause current sheet: thickness, length, scale and controlling factors, *J. Geophys. Res.*, 86, 11430–11438.

Frisch, U. (1995), *Turbulence, the legacy of A.N. Kolmogorov*, Cambridge University Press.

Intriligator, D.S., H.R. Collard, J.D. Mihalov, R.C. Whitten, and J.H. Wolfe (1979), Electron observations and ion flow from the Pioneer Venus Orbiter Plasma Analyzer Experiment, *Science*, 205, 116–119.

Leubner, M. P. and Vörös, Z. (2005), A nonextensive entropy approach to solar wind intermittency, *Astrophys. J.*, 618, 547–555.

Luhmann, J. G., and C.T. Russell (1983), Magnetic fields in the ionospheric holes of Venus: evidence for an intrinsic field? in *Geophys. Res. Lett.*, 10, 409–412.

Luhmann, J. G., C. T. Russell, K. Schwingenschuh, and Y. Yeroshenko (1991), A comparison of induced magnetotails of planetary bodies: Venus, Mars and Titan, *J. Geophys. Res.*, 96, 11199–11208.

Luhmann, J.G., M. Tatrallyay, C. T. Russell, and D. Winterhalter (1983), Magnetic field fluctuations in the Venus magnetosheath, *Geophys. Res. Lett.*, 10, 655–658.
Marubashi, K., J.M. Grebowsky, H.A. Taylor, J.G. Luhmann, C.T. Russel, and A. Barnes (1985) Ionosheath plasma flow in the wake of Venus and the formation of ionospheric holes, *J. Geophys. Res.*, 90, 1385–1398.

Pérez-de-Tejada, H., D.S. Intriligator, and R.J. Strangeway (1991), Steady-state plasma transition in the Venus ionosheath, *Geophys. Res. Lett.*, 18, 131–134.

Pérez-de-Tejada, H., D.S. Intriligator, and R.J. Strangeway (1993), Magnetic field properties of the intermediate transition of the Venus ionosheath, *Geophys. Res. Lett.*, 20, 991–994.

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling (1992), Numerical recipes in C: The art of scientific computing, Cambridge University Press.

Romanov, S., V. Smirnov, and O. Vaisberg (1978), Interaction of the solar wind with Venus, *Kosmich. Issled.*, 16, 746.

Russell, C.T. (1992), The Pioneer Venus mission, in. Venus and Mars: Atmospheres, Ionospheres and Solar Wind Interactions, *AGU Geophys Monogr. Series*, 66, (eds. J. G. Luhmann, M. Tatrallyay, and R. O. Repin), 225–236.

Russell, C.T., and O. Vaisberg (1983), The interaction of the solar wind with Venus, *Venus*, (eds. D.M. Hunton, L Colin, T.M. Donahue, V.I. Moroz), 873–940.

Spreiter, J. R., and S.S. Stahara (1992), Computer modeling of solar wind interaction with Venus and Mars, in. Venus and Mars: Atmospheres, Ionospheres and Solar Wind Interactions, *AGU Geophys Monogr. Series*, 66, (eds. J. G. Luhmann, M. Tatrallyay, and R. O. Repin), 345–383.

Terada, N., S. Machida, and H. Shinagawa (2002), Global hybrid simulation of the Kelvin-Helmholtz instability at the Venus ionopause, *J. Geophys. Res.*, 107(A12), 1471,
doi:10.1029/2001JA009224.

Volwerk, M., T.L. Zhang, M. Delva, Z. Vörös, W. Baumjohann and K.-H. Glassmeier (2008a), First identification of mirror mode waves in Venus’ magnetosheath? *Geophys. Res. Lett.*, 35, L12204, doi:10.1029/2008GL033621.

Volwerk, M., T.L. Zhang, M. Delva, Z. Vörös, W. Baumjohann and K.-H. Glassmeier (2008b), A statistical study of mirror mode like structures in Venus’ magnetosheath, submitted to *J. Geophys. Res.*.

Vörös, Z. et al. (2004), Magnetic turbulence in the plasma sheet, *J. Geophys. Res.*, 109, A11215, doi:10.1029/2004JA010404.

Vörös, Z., W. Baumjohann, R. Nakamura, A. Runov, M. Volwerk, T. Takada, E. A. Lucek, and H. Rème (2007), Spatial structure of plasma flow associated turbulence in the Earth’s plasma sheet, *Ann. Geophys.*, 25, 13–17.

Vörös, Z., T.L. Zhang, M. P. Leubner, M. Volwerk, M. Delva, W. Baumjohann and K. Kudela (2008), Magnetic fluctuations and turbulence in the Venus magnetosheath and wake, *Geophys. Res. Lett.*, 35, L11102, doi:10.1029/2008GL033879.

Wolff, R., B. Goldstein, and C. Yeates (1980), The Onset and Development of Kelvin-Helmholtz Instability at the Venus Ionopause, *J. Geophys. Res.*, 85(A13), 7697-7707.

Yordanova, E., A. Vaivads, M. Andr, S.C. Buchert, and Z. Vörös (2008), Magnetosheath plasma turbulence and its spatiotemporal evolution as observed by the Cluster spacecraft *Phys.Rev.Lett.*, 100, 205003-1–205003-4.

Zhang Z.L., et al. (2006), Magnetic field investigation of the Venus plasma environment: Expected new results from Venus Express, *Planet.Space Sci.*, 54, 1336–1343.
Zhang T.L., et al. (2007), Little or no solar wind enters Venus atmosphere at solar minimum, *Nature*, 450, 654–656, doi:10.1038/nature06026.
Figure 1. Top: Magnetic field strength (B) on May 19, 2006. The horizontal black lines correspond to the time intervals a - e of equal length in the dayside magnetosheath (a), night side near-planet wake (b), magnetosheath boundary layer (c), tailward magnetosheath (d), and in the vicinity of the bow shock; Bottom: Power spectra and spectral scalings estimated within the intervals a - e. Pronounced wavy structures are present mainly in the wake (interval b). The vertical arrow points to the spectral peak at $\sim 15$ s.
**Figure 2.** Top left: Magnetic field strength ($B$, grey line) and $B_X$ magnetic component (black line) on May 19, 2006; the horizontal lines show the intervals a-e depicted in Figure 1; Bottom left: VEX crossings (thin black lines) of the Venusian plasma environment in VSO coordinates. The intervals a-e (black lines) are shown alongside the VEX trajectories. The filled circles show the bow shock, the open circles show the magnetopause during multiple crossings (after Zhang et al., 2007). The large triangles along the lowest trajectory correspond to the region of wavy structures and spectral scaling index $\alpha \sim 2.5$.

The family of thick black lines along the trajectories (intervals c and e) correspond to turbulent regions with $\alpha \sim 1.6$. The grey '+' signs are intervals of $1/f$ noise (interval d); Right: Enlarged magnetosheath crossings in VSO coordinates. The same notations is used as in the left. The bottom right subplot shows the approximate spatial size of the turbulent (c, e) and noisy (d) regions in space.
Figure 3. Histograms of the scaling indices in different regions of near-Venusian space (approximately obtained during the intervals a-e in Figure 2.). From top to bottom: dayside magnetosheath (a); near and post-terminator wake (b); magnetosheath boundary and near bow shock region (c-e); post-terminator tailward magnetosheath (d). These spatial regions are depicted more clearly in Figure 4.
Figure 4. A cartoon showing the type of physical processes in the spatial regions of near-Venusian space; the magnetopause and the bow shock (dashed lines); a VEX crossing (solid black line); the optical shadow (shaded region); draped IMF (thin black line); the time intervals/spatial regions a-e are marked with squares, triangles, circle, squares, and circle, respectively.
Figure 5. From top to bottom: comparison of 12 min averages of $\langle b_x^2 \rangle$, $\langle b_y^2 \rangle$, and $\langle b_z^2 \rangle$ with the observed spectral scaling indices $\alpha$; The subscripts indicate VSO magnetic field components; The horizontal lines correspond to averages of points (open and filled circles) over the noisy $\alpha \in (0.6 - 1.4)$ and turbulent $\alpha = 1.6 \pm 0.2$ scaling index ranges in each subplot; The turbulent intervals include boundary layer (filled circles) and near-shock (open circles) events; For each 12 min interval $b_x^2(t) + b_y^2(t) + b_z^2(t) = 1$. 
PDF

Boundary turbulence

1/f noise in the magnetosheath

Figure 6. Probability density functions (PDFs) constructed from magnetic time series (two-point differences defined through $\delta B = B(t + \tau) - B(t)$) of turbulent (left) and noisy (right) intervals. Gaussian fits are shown as dashed grey lines. At small scales (e.g. $\tau = 3$ s) the PDF is a non-Gaussian for turbulent time series and Gaussian for noisy time series. At large scales (e.g. $\tau = 30$ s) the PDF is a Gaussian in both cases. The error bars represent 95% confidence limits for the mean in each point of $\delta B_T$. 
Figure 7. The evolution of kurtosis ($K$, top) and skewness ($S$, bottom) with the time scale $\tau$, computed from two-point differences defined through $\delta B = B(t + \tau) - B(t)$ of turbulent (left) and noisy (right) time intervals. $K$ - peakedness of the PDF; $S$ - asymmetry around the mean, both relative to a Gaussian distribution, for which $S = K = 0$; The error bars represent 95% confidence limits for the mean in each value of $\tau$. 