AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL104610

Shocklets and Short Large Amplitude Magnetic Structures (SLAMS) in the High Mach Foreshock of Venus

Glyn A. Collinson[1,2], Heli Hietala[3], Ferdinand Plaschke[4], Tomas Karlsson[5], Lynn B. Wilson III[1], Martin Archer[6], Markus Battarbee[7], Xochitl Blanco-Cano[8], Cesar Bertucci[9], David Long[10], Merav Opher[11], Nick Sergis[12], Claire Gasque[13], Terry Liu[14], Savvas Raptis[5,15], Sofia Burne[9], Rudy Frahm[16], Tielong Zhang[17], and Yoshifumi Futaana[18]

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [2]The Catholic University of America, Washington, DC, USA, [3]School of Physical and Chemical Sciences, Queen Mary, University of London, London, UK, [4]Technische Universität Braunschweig, Braunschweig, Germany, [5]Division of Space and Plasma Physics, KTH Royal Institute of Technology, Stockholm, Sweden, [6]Faculty of Natural Sciences, Department of Physics, Imperial College London, London, UK, [7]Space Physics Research Group, University of Helsinki, Helsinki, Finland, [8]Instituto de Geofísica, Universidad Nacional Autónoma de México, Mexico City, Mexico, [9]Institute for Astronomy and Space Physics (IAFE), UBA CONICET, Buenos Aires, Argentina, [10]Astrophysics Research Centre, Queen's University Belfast, Belfast, UK, [11]Department of Astronomy, Boston University, Boston, MA, USA, [12]Hellenic Space Center, Chalandri, Greece, [13]Space Sciences Laboratory, University of California, Berkeley, CA, USA, [14]Department of Earth Planetary and Space Sciences, University of California, Los Angeles, Los Angeles, CA, USA, [15]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA, [16]Southwest Research Institute, San Antonio, TX, USA, [17]Space Research Institute, Austrian Academy of Sciences, Graz, Austria, [18]Institutet för Rymdfysik, Kiruna, Sweden

Key Points:

- Shocklets and short large-amplitude magnetic structures (SLAMS) can form in the steady-state foreshock of Venus despite the magnetosphere being 1/10th the size of Earths
- The Venusian Shocklets and SLAMS had comparable magnetic signatures to those reported near Earth, but may be rarer
- Analysis of the solar wind at 0.72AU suggests Shocklets and SLAMS occur during high Alfvén mach-numbers with a lower limit on occurrence rate of ≳14%

Correspondence to:

G. A. Collinson,
glyn.a.collinson@nasa.gov

Citation:

Collinson, G. A., Hietala, H., Plaschke, F., Karlsson, T., Wilson, L. B., III, Archer, M., et al. (2023). Shocklets and short large amplitude magnetic structures (SLAMS) in the high mach foreshock of Venus. *Geophysical Research Letters*, *50*, e2023GL104610. https://doi.org/10.1029/2023GL104610

Received 17 MAY 2023
Accepted 12 SEP 2023

Abstract Shocklets and short large-amplitude magnetic structures (SLAMS) are steepened magnetic fluctuations commonly found in Earth's upstream foreshock. Here we present *Venus Express* observations from the 26th of February 2009 establishing their existence in the steady-state foreshock of Venus, building on a past study which found SLAMS during a substantial disturbance of the induced magnetosphere. The Venusian structures were comparable to those reported near Earth. The 2 Shocklets had magnetic compression ratios of 1.23 and 1.34 with linear polarization in the spacecraft frame. The 3 SLAMS had ratios between 3.22 and 4.03, two of which with elliptical polarization in the spacecraft frame. Statistical analysis suggests SLAMS coincide with unusually high solar wind Alfvén mach-number at Venus (12.5, this event). Thus, while we establish Shocklets and SLAMS can form in the stable Venusian foreshock, they may be rarer than at Earth. We estimate a lower limit of their occurrence rate of ≳14%.

Plain Language Summary We discover that Venus, like Earth, also has magnetic structures called Shocklets and short large-amplitude magnetic structures (SLAMS) in its foreshock region, which is the area upstream of the planet where the interplanetary magnetic field is connected to its bow shock. Shocklets and SLAMS are common in the foreshock of Earth. However, Shocklets have not been observed at Venus before, and SLAMS have only been seen once, and then only during a large disturbance of the space near Venus. Thus it is unknown if SLAMS and Shocklets can form in the foreshock of a planet as close to its star as Venus. We used observations from the European Space Agency's *Venus Express* orbiter (2006–2014) to identify these structures in the Venusian foreshock. The structures were found to be present during periods of high solar wind activity, and a lower limit on how often they occur is at least 14% of the time. These findings provide new insights into the space environment around Venus and may help us understand the differences in the space environments of different planets.

1. Introduction

1.1. The Field of Ultra-Low-Frequency (ULF) Waves Upstream of Venus

A foreshock is the region that forms upstream of any planetary supersonic bow shock where the interplanetary magnetic field (IMF) is magnetically connected to the bow shock, that is, parallel to the shock normal ($\theta_{B.\hat{n}} < 45°$) (Eastwood, Lucek, et al., 2005). Under these conditions, and as long as the Alfvén Mach number exceeds ≈4 (Thomsen et al., 1993), ions reflected at the bow shock can escape back upstream. The resulting ion beam instabilities generate a field of ultra-low-frequency (ULF) waves which pervade the foreshock region (Fairfield, 1969;

Scarf et al., 1970). They are often referred to as "30 s waves" (Eastwood, Balogh, et al., 2005) due to their typical period at Earth (in the spacecraft frame), which comes from the strength and cone angle of the interplanetary magnetic field (Takahashi et al., 1984). A similar field of 30 s ULF waves was discovered upstream of Venus by Greenstadt et al. (1987). They found the general morphology of the Venusian foreshock ULF wave field is similar to that at Earth despite the vastly different scale sizes of the planetary bow shocks. Statistical analysis by Shan et al. (2018) revealed their mean frequency to be 20–30 s in the spacecraft frame (similar to Earth), 2 to 3 times the local proton cyclotron period. As at Earth, foreshock ULF waves originate in the quasi-parallel region of the Venusian foreshock (Omidi et al., 2017).

ULF waves attempt to propagate upstream from the planet they are generated near but are blown back toward the bow shock by the solar wind. As they move deeper into the foreshock, they encounter higher levels of superthermal ion density. These ions modify the refractive index of the medium, causing the transverse modes to become compressive, leading to the waves steepening (Tsubouchi & Lembège, 2004; Tsurutani et al., 1987; L. B. Wilson III et al., 2009). The waves become more oblique and compressive as they penetrate deeper into the foreshock. Two foreshock phenomena which can result from this steepening of ULF waves are (a) Shocklets (Hoppe & Russell, 1981) and (b) Short large-amplitude magnetic structures (SLAMS) (Chen et al., 2021; Schwartz, 1991).

1.2. Shocklets

1.2.1. Characteristics of Shocklets

As ULF waves are advected toward the bow shock, they can quickly grow to nonlinear amplitudes (Dorfman et al., 2017), undergoing steepening into "Shocklets." Shocklets are magnetosonic magnetic structures with the following characteristics; (a) Magnetic compression ratio (dB/B_0) between 1 and 2 (L. B. Wilson et al., 2013); (b) Have a steepened upstream edge giving a "saw tooth" profile (Bertucci et al., 2007); (c) typically display linear polarization (Hoppe & Russell, 1981); and (d) dispersively radiate higher frequency electromagnetic whistler precursor waves as they steepen (L. B. Wilson et al., 2013).

1.2.2. Where Have Shocklets Been Observed Previously?

Shocklets were first reported at Earth by Hoppe and Russell (1981) and have since been observed at other magnetospheres including upstream of Jupiter (Tsurutani et al., 1993) and Saturn (Andrés et al., 2013; Bertucci et al., 2007). However, no Shocklets have been previously reported at Venus despite extensive exploration of the Venusian ULF wave field by NASA's *Pioneer Venus Orbiter* (1978–1992) and ESA's *Venus Express* orbiter (2006–2014).

1.3. Short Large-Amplitude Magnetic Structures (SLAMS)

1.3.1. Characteristics of SLAMS

Another non-linear magnetosonic structure that can evolve from the ULF wave field are Short Large-Amplitude Magnetic Structures (SLAMS) (Schwartz, 1991). SLAMS are characterized at Earth by Equation 1 Magnetic compression ratio (dB/B_0) of at least twice the background field (and sometimes being as high as $dB/B_0 = 5$) (Schwartz, 1991; Schwartz et al., 1992; L. B. Wilson et al., 2013); (b) Brief ($5 - 20$s) monolithic spikes in magnetic field magnitude ($|B|$); (c) Elliptical polarization in the plasma frame (but can be observed as linear polarized in the spacecraft frame) (Dubouloz & Scholer, 1993; Schwartz, 1991; Schwartz et al., 1992; Tsurutani et al., 1993).

1.3.2. Where Have SLAMS Been Observed Previously?

The first extraterrestrial report of "*steepened magnetosonic waves*" consistent with SLAMS was made by Tsurutani et al. (1987), who used data from the *International Comet Explorer* spacecraft during its intercept with Comet Giacobini-Zinner on the 11th of September 1985 at a distance from the Sun of 1.03AU. SLAMS-like structures have subsequently been reported at Mars (Collinson et al., 2018; Fowler et al., 2018; Halekas et al., 2017; Shuvalov & Grigorenko, 2023) (~1.52 AU), Jupiter (Tsurutani et al., 1993) (~5.2 AU), and Saturn (Bebesi et al., 2019) (~9.54 AU).

To date, the only report of SLAMS forming sunward of Earth is by Collinson, Wilson, et al. (2012), who presented a case study of 3 SLAMS upstream of the bow shock of Venus (0.72 AU). However, these were associated with a transient event in the foreshock driven by a discontinuity in the interplanetary magnetic field (possibly a Hot Flow Anomaly (Collinson, Sibeck, et al., 2014) or similar). This foreshock transient substantially perturbed the Venusian induced magnetosphere, driving the bow shock outwards from its typical location by ≈3,000 km. Thus, SLAMS have only been reported at Venus during a substantial disturbance of the foreshock and induced magnetosphere. It is unclear if they can exist in the steady-state foreshock of Venus, when the solar wind, interplanetary magnetic field, and magnetosphere are quiescent.

1.4. Objectives and Overview of This Paper

The dearth of observations of Shocklets and SLAMS in the steady-state foreshock of Venus calls into question whether they can form at such small magnetospheres under quiescent upstream conditions. Given that at Venus the bow shock is an order of magnitude smaller than at Earth it is not obvious whether ULF waves will have sufficient time and space to grow nonlinear and steepen into Shocklets and SLAMS. Thus, understanding under what conditions the Venusian foreshock can intrinsically generate such structures would be important for our understanding how stellar winds interact with small bow shocks, such as those found at planets and moons with induced magnetospheres (e.g., Venus, Mars, Titan), Comets, and worlds with weak magnetic dipoles (e.g., Mercury).

Here we present a case study of in situ observations by ESA's *Venus Express* orbiter from the 26th of February 2009, demonstrating the existence of both Shocklets and SLAMS in the steady-state foreshock and ULF wave field of Venus. We use data from the *Venus Express* Magnetometer (Zhang et al., 2006) and Analyzer for Space Plasmas and Energetic Atoms (ASPERA-4) Ion Mass Analyzer (IMA) (Barabash et al., 2007) and Electron Spectrometer (ELS) (Collinson et al., 2009).

Our paper is outlined as follows. In Section 2 we give a brief review of the induced magnetosphere and foreshock of Venus. In Section 3 we describe the *Venus Express* instruments used in this study. In Section 4 we describe orbit №1043 and give an overview of what conditions were like in the quasi-parallel magnetosheath and foreshock. In Section 5 we describe our analysis of the 5 events (3 SLAMS and 2 Shocklet candidates). In Section 6 we describe statistical analysis of solar wind measurements by the *Venus Express*, finding that SLAMS and Shocklets may not be common at Venus. Finally in Section 7 we summarize our findings and conclusions.

2. The Venusian Induced Magnetosphere and Foreshock

Without an intrinsic magnetic dipole (Smith et al., 1965) the obstacle to the solar wind at Venus is its dense and conductive ionosphere. The advection of the interplanetary magnetic field induces electrical currents within the ionosphere. These currents generate a global system of weak and overlapping induced magnetic fields (Dubinin et al., 2013). The resulting induced magnetosphere is far weaker than at Earth and roughly an order of magnitude smaller (Bertucci et al., 2011; Futaana et al., 2017; Luhmann, 1990). The Venusian bow shock stands off only ≈1.4 Venus Radii (R_V) upstream from the center of the planet (Slavin et al., 1980) (Figure 1g), as compared to $\approx 15R_E$ at Earth (Fairfield, 1971). Behind the Venusian bow shock is the Magnetosheath (sometimes called the Ionosheath), a region of shock-heated solar wind. For more information on the structure of the Venusian magnetosphere (which has been recently revised in light of new data from *Parker Solar Probe*), see Collinson, Ramstad, et al. (2022).

The Venusian foreshock can extend for several R_V upstream of the planet, especially when the interplanetary magnetic field is aligned with the Venus-Sun axis (Collinson et al., 2020; Luhmann et al., 1986; Omidi et al., 2017). Our current understanding is that the Venusian foreshock is similar to Earth's, albeit in miniature, containing the same transient phenomena, including ULF Waves (Dubinin & Fraenz, 2016; Fränz et al., 2017; Greenstadt et al., 1987), Foreshock Whistler "1 Hz" waves (Collinson et al., 2015; Orlowski et al., 1990), Hot Flow Anomalies (Collinson, Sibeck, et al., 2012; Collinson, Sibeck, et al., 2014), Spontaneous Hot Flow Anomalies (Collinson et al., 2017), Foreshock Bubbles (Omidi et al., 2020), Foreshock Cavities (Collinson et al., 2020), and now SLAMS and Shocklets (This Study). Venus has an additional source of upstream waves (compared to Earth), which can arise from the pickup of ions from the exosphere which at Venus extends into the solar wind (Delva et al., 2015).

3. *Venus Express* Instrumentation

The primary instrument used in this study is the *Venus Express* magnetometer (MAG) (Zhang et al., 2006), which measured 3D ambient magnetic fields at cadences of up to 128 Hz. In this study, standard survey data (4s) as well

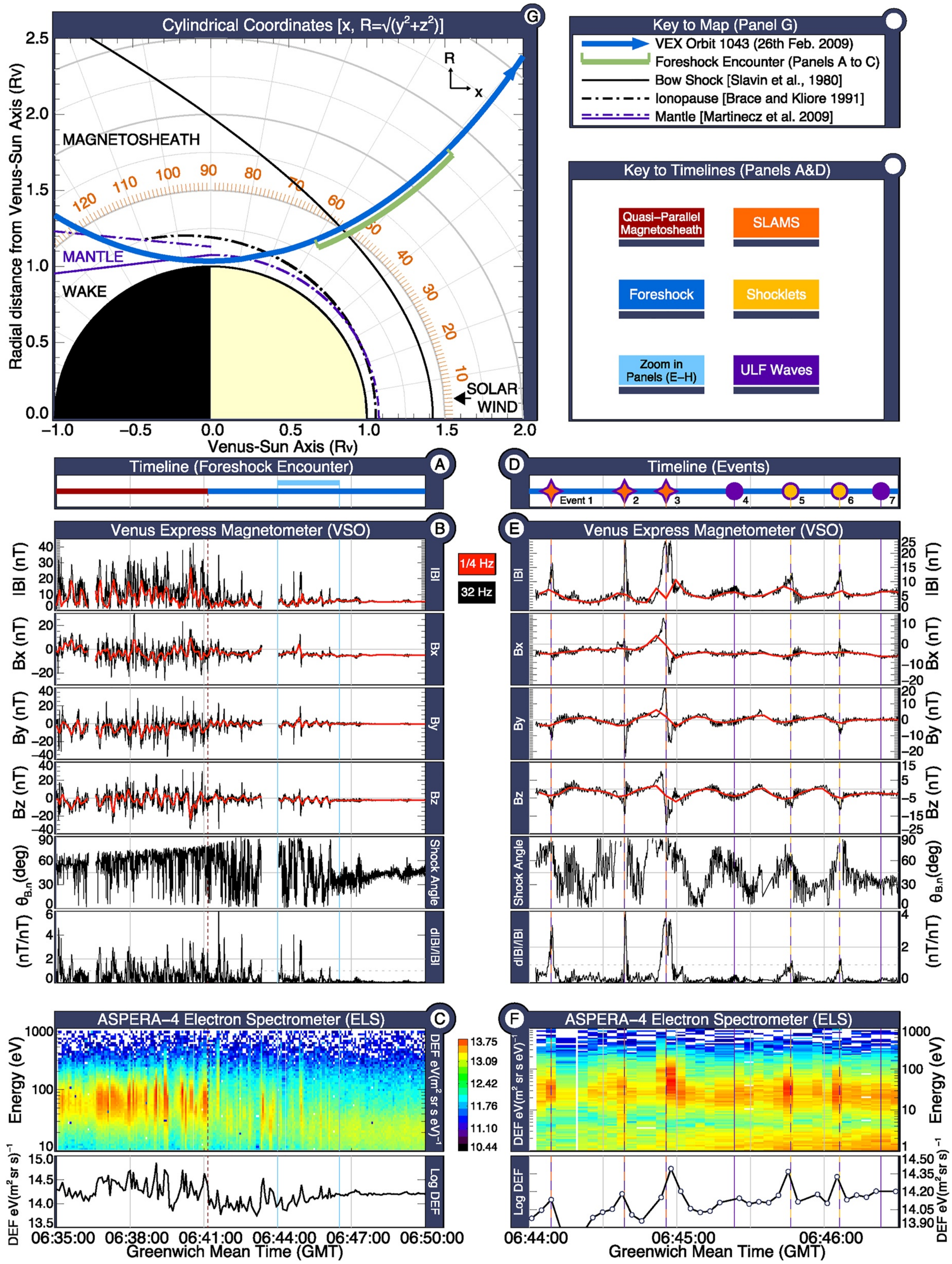
Cylindrical Coordinates [x, R=√(y²+z²)]
Key to Map (Panel G)
VEX Orbit 1043 (26th Feb. 2009)
Foreshock Encounter (Panels A to C)
Bow Shock [Slavin et al., 1980]
Ionopause [Brace and Kliore 1991]
Mantle [Martinecz et al. 2009]
Key to Timelines (Panels A&D)
Quasi–Parallel Magnetosheath
SLAMS
Foreshock
Shocklets
Zoom in Panels (E–H)
ULF Waves
MAGNETOSHEATH
MANTLE
WAKE
SOLAR WIND
Radial distance from Venus-Sun Axis (Rv)
Venus-Sun Axis (Rv)
Timeline (Foreshock Encounter)
Timeline (Events)
Venus Express Magnetometer (VSO)
1/4 Hz
32 Hz
ASPERA–4 Electron Spectrometer (ELS)
Greenwich Mean Time (GMT)

Figure 1.

as high-resolution (32 Hz) data is used. This study is supported by measurements of electrons and ions by the Analyzer for Space Plasmas and Energetic Atoms (ASPERA-4) (Barabash et al., 2007; Collinson et al., 2009). ASPERA-ELS measured the energy spectra of electrons between 1 eV and 21 keV at a cadence of either 1s or 4s. This study also uses solar wind measurements by the ASPERA-4 Ion Mass Analyzer (IMA) instrument, which measured the velocity distributions of ions between 12 eV and 30 keV. ASPERA-IMA had a broad 3D field of view (90° × 360°), and the ability to separate ions by mass group (H^+, He^+, "Heavy ions"). However, ASPERA-IMA had a very slow (192 s) measurement cadence, and as will be shown in Section 6, tended to under-estimate solar-wind densities.

4. *Venus Express* Explores the Venusian Foreshock on 26 February 2009

Figure 1g shows a map of *Venus Express* orbit №1043, occurring on the 26th of February 2009. Figures 1a–1f show in situ measurements from this orbit. Two time periods are shown. Figures 1a–1c shows an overview of the entire encounter with the foreshock so that the events described in this paper can be put into context. Figures 1d–1f shows a close up of 2 min 30 s of data containing Shocklets and SLAMS where we shall focus our analysis. Figures 1a and 1d show color coded timelines of each of these two periods. Magnetometer (Mag) data (Figures 1b and 1e) are presented in the Venus Solar Orbital (VSO) coordinate system, where x points toward the sun, y points back along the orbital path of the planet perpendicular to the Venus-Sun line opposite to the planet's velocity vector, and z points out of the plane of the ecliptic completing the right-hand set. The angle between the magnetic field and bow-shock normal ($\theta_{B.\hat{n}}$, Figures 1b and 1e) was calculated by propagating the IMF field line direction at the location of *Venus Express* until it intersects the Slavin et al. (1980) bow shock model. The magnetic compression ratio (dB/B_0) was calculated by subtracting the 32 Hz data from the time-averaged 1/4 Hz data (B_0).

Data from the foreshock encounter (Figures 1a–1c) reveal there was no clear boundary delineation between the magnetosheath (maroon) and foreshock (dark blue). Large amplitude waves were observed throughout the period (Figure 1b). These waves were of approximately the same amplitude (30–40 nT) until ≈06:41, after which they generally tended to reduce in amplitude with increasing distance from the planet. We thus estimate 06:41 GMT as an approximate transition between being more in the sheath to being more in the foreshock, based also on a change in energy spectra from ASPERA-4 ELS (Figure 1c). These data are very consistent with the complex field of steepened magnetosonic waves expected in the quasi-parallel sheath and foreshock (Collinson et al., 2020; Luhmann et al., 1987; Shan et al., 2014). Thus, we conclude *Venus Express* transitioned between quasi-parallel magnetosheath to foreshock sometime after 06:41 GMT on the 26 of February 2009, and was thus in the right place to search for SLAMS and Shocklets.

5. SLAMS and Shocklets at Venus

For the remainder of this paper we shall focus on magnetic fluctuations observed between 06:44:00 and 06:46:30 GMT (light blue on Figure 1a timeline); 3 SLAMS (orange stars, Event №1, №2, №3); 2 Shocklets (Gold Circle, Event №5, №6); and 2 non-steepened ULF waves (Purple Circle, Event №4, №7) for comparison. These events were classified according to their compression ratios ($\delta B/B_0$).

5.1. Magnetometer

5.1.1. Overview of Observations

A time-series of Magnetometer data are shown in Figures 1b and 1e at two cadences; at 32 Hz (black) to better resolve the details of the magnetic perturbations; and at 1/4 Hz (bright red) to more clearly see the general trends in the background field. The first three events (№1, №2, №3) are highly compressive, all with $dB/B_0 > 3$,

Figure 1. *Venus Express* field and particle observations from orbit №1043, 26th of February 2009. Panels (a–c) show data from the period 06:35 to 06:50, the time interval marked "Encounter" in (g), covering the transition from magnetosheath to foreshock. Panels (d–f) show a zoom-in of the region of interest (06:44:00 to 06:46:30) where 3 SLAMS and 2 Shocklets candidates were encountered. Panels (a and d) show a color-coded timeline. Panels (b and e) show magnetometer (MAG) data at 32 Hz (black) and 1/4 Hz (red) cadence. From top to bottom; magnetic field magnitude (|B|) in nT; Vector (Bx, By, Bz, in VSO coordinates) in nT; the angle between the magnetic field and bow-shock normal ($\theta_{B.\hat{n}}$); and the compression ratio of the magnetic field (dB/B_0). Panels (c and f) show data from ASPERA-ELS, with time/energy spectrograms on top and the total measured superthermal Differential Energy Flux (DEF) below. Panel (g) shows a map of *Venus Express* orbit №1043 through the induced magnetosphere of Venus in units of Venus Radii ($R_V = 6051.8\ km$).

consistent with SLAMS. The compression ratio of event №2 was greater than the maximum factor of four for simple compression (Gurnett & Bhattacharjee, 2005), also highly indicative of SLAMS (Schwartz et al., 1992).

The latter two events (№5 and №6) were less steep, with compression ratios between $1 < dB/B_0 \leq 2$, consistent with Shocklets. These two steepened waves were observed between two ULF waves (№4, 7). Given all four were observed at a regular cadence of 20 ± 3s consistent with the period expected from the Venusian wave field (Shan et al., 2018), this suggests that the events №5 and №6 grew as a direct result of the steepening of "30 s" ULF waves, as expected for Shocklets.

5.1.2. Minimum Variance Analysis of Venusian SLAMS and Shocklets

Following L. B. Wilson III et al. (2009) we performed minimum variance analysis (MVA) (Sönnerup & Scheible, 1998) on each of the 3 SLAMS and 2 Shocklets using frequency filters to determine the characteristics of each magnetic structure. Figure 2 shows a close-up of magnetometer data from each of the events. The top panel shows calibrated magnetometer data at 32 Hz in VSO coordinates (black, as per Figures 1b and 1e). The bright red line shows these data with a $0.004 \rightarrow 0.5$ Hz filter applied. The lower panels of Figure 2 show hodograms of these filtered subintervals of data after MVA. Table 1 accompanies Figure 2, showing the collected properties of each of the events, including the results of MVA analysis.

SLAMS: The top three panels (A, B, C) of Figure 2 show close-ups of the three SLAMS candidates. The mean compression ratio of the SLAMS (dB/B_0) was 3.7 times the background field, and they had periods between ≈2 → 6 s. The first SLAMS (Event №1) was linearly polarized in the spacecraft frame. The second and third SLAMS candidates (Event №2 and №3) were elliptically polarized in the spacecraft frame, consistent with previous observations of SLAMS (Dubouloz & Scholer, 1993; Mann et al., 1994). With only a single spacecraft we cannot determine the propagation direction. Of the three SLAMS candidates, event №2 exhibited the most circular polarization with MVA eigenvalues $\lambda_{mid}/\lambda_{\min} = 352$ and $\lambda_{\max}/\lambda_{mid} = 1.8$. Most of the five events are associated with a train of whistler waves, consistent with either SLAMS or Shockets which act as a localized miniature bow shock. Of the SLAMS candidates, Event №3 shows the best example of a classical wave train of precursor whistlers on the upstream side, consistent with previous observations of SLAMS at Earth (L. B. Wilson et al., 2013) and Saturn (Bebesi et al., 2019). Our MVA analysis shows the three SLAMS candidates had an average angle between wave vector and the magnetic field of $\theta_{\hat{\mathbf{k}}\langle\hat{\mathbf{b}}\rangle} \approx 71°$. These structures are thus compressive and obliquely propagating to the ambient magnetic field consistent with previous observations of SLAMS at Earth (Chen et al., 2021; Mann et al., 1994).

Shocklets: The bottom two panels (D, E) of Figure 2 show close-ups of the two Shocklets candidates. Both have the classical asymmetrical "saw-tooth" profile of a Shocklet, with a steeper edge on the upstream (trailing) side (Hoppe & Russell, 1981). The mean compression ratio was 1.29, and both were linearly polarized, also consistent with what is expected of Shocklets (L. B. Wilson et al., 2013). The two Shocklets had a similar $\theta_{\hat{\mathbf{k}}\langle\hat{\mathbf{b}}\rangle}$ of ≈78°, which, again, is highly consistent with a fast magnetospheric mode structure such as a Shocklet.

5.2. Observations of Associated Plasma Perturbations by the Electron Spectrometer (ASPERA-4 ELS)

A feature of compressive magnetosonic structures such as SLAMS and Shocklets is that they act like a local quasi perpendicular shock, locally perturbing the solar wind, and increasing both $|B|$ and plasma density (Behlke et al., 2003; Collinson et al., 2018; Dubouloz & Scholer, 1993; Mann et al., 1994). However, the previous study of SLAMS at Venus by Collinson, Wilson, et al. (2012) were unable to examine the plasma perturbations anticipated from SLAMS. Figures 1c and 1f show measurements of superthermal electron flux from ASPERA-4 ELS, with a time/energy spectrogram on top and line-plot of total integrated superthermal electron flux at the bottom. Electron flux remained fairly constant during the two ULF waves (event №4 and №7). However electron flux was enhanced in phase with $|B|$ at all 3 SLAMS and both Shocklets, consistent with such steepened magnetosonic structures.

6. How Common Are SLAMS and Shocklets at Venus?

SLAMS have now been reported at Venus on two days: 11 April 2009 (Collinson, Wilson, et al., 2012) and 26 February 2009 (this study). A thorough statistical determination of the occurrence rate would require more than 2 events. However, following Collinson, Sibeck, et al. (2014) and Collinson, Fedorov, et al. (2014), we can put a

10.1029/2023GL104610

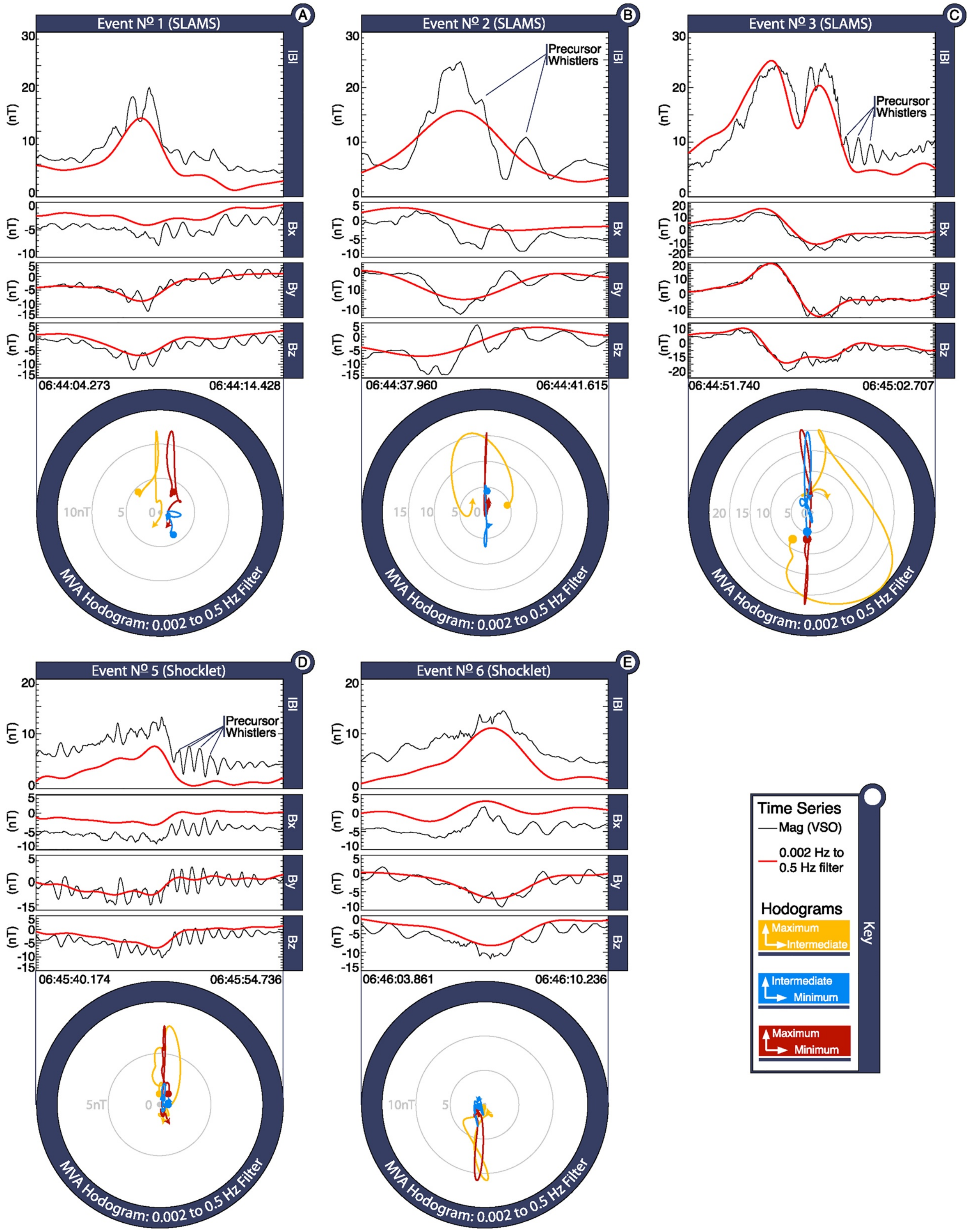

Figure 2. Close up view of the 3 SLAMS and 2 Shocklet candidates from Figures 1e–1h. Top Panels: time series showing original data and filtered between 0.002 and 0.5 Hz. Bottom Panels: Hodogram of Minimum Variance Analysis of magnetometer data filtered between 0.002 and 0.5 Hz.

Table 1
Table Showing Properties of the 5 Steepened Magnetosonic Structures Show in Fig

Event №	Classification	Start (GMT)	Duration (s)	dB/B_0	Polarization (S/C frame)	$\theta_{\hat{k}\langle\hat{b}\rangle}$	$\frac{\lambda_{mid}}{\lambda_{min}}$	$\frac{\lambda_{max}}{\lambda_{mid}}$
1	SLAMS	06:44:07	3.5 s	3.22	Linear	64.91°	3.82	13.21
2	SLAMS	06:44:38	2.0 s	4.03	Elliptical	89.27°	352.38	1.84
3	SLAMS	06:44:52	6.2 s	3.59	Elliptical	58.60°	95.23	3.17
5	Shocklet	06:45:40	8.4 s	1.23	Linear	78.71°	12.20	18.93
6	Shocklet	06:46:05	3.5 s	1.34	Linear	77.07°	9.14	7.88

Note. Duration was calculated by eye from the apparent start and stop time of the magnetic signature. Polarization was determined by eye from the hodogram in Figure 2.

lower limit on their occurrence rate through investigation of whether the conditions in the solar wind upstream of Venus were unusual on these 2 days. Specifically, we examine the solar wind Alfvén Mach number (M_A), which is thought to be a general requirement for SLAMS formation at Earth ($M_A \geq 4$) to reflect ions at the bow shock and set up the ion-ion beam instabilities that lead to ULF wave formation (Thomsen et al., 1993) from which SLAMS form.

Figure 3 shows histograms of the upstream conditions at Venus from the entire 2006–2014 *Venus Express* mission (black). The data are further divided into two types: "slow" solar wind (with bulk velocities <500 km s^{-1}) and

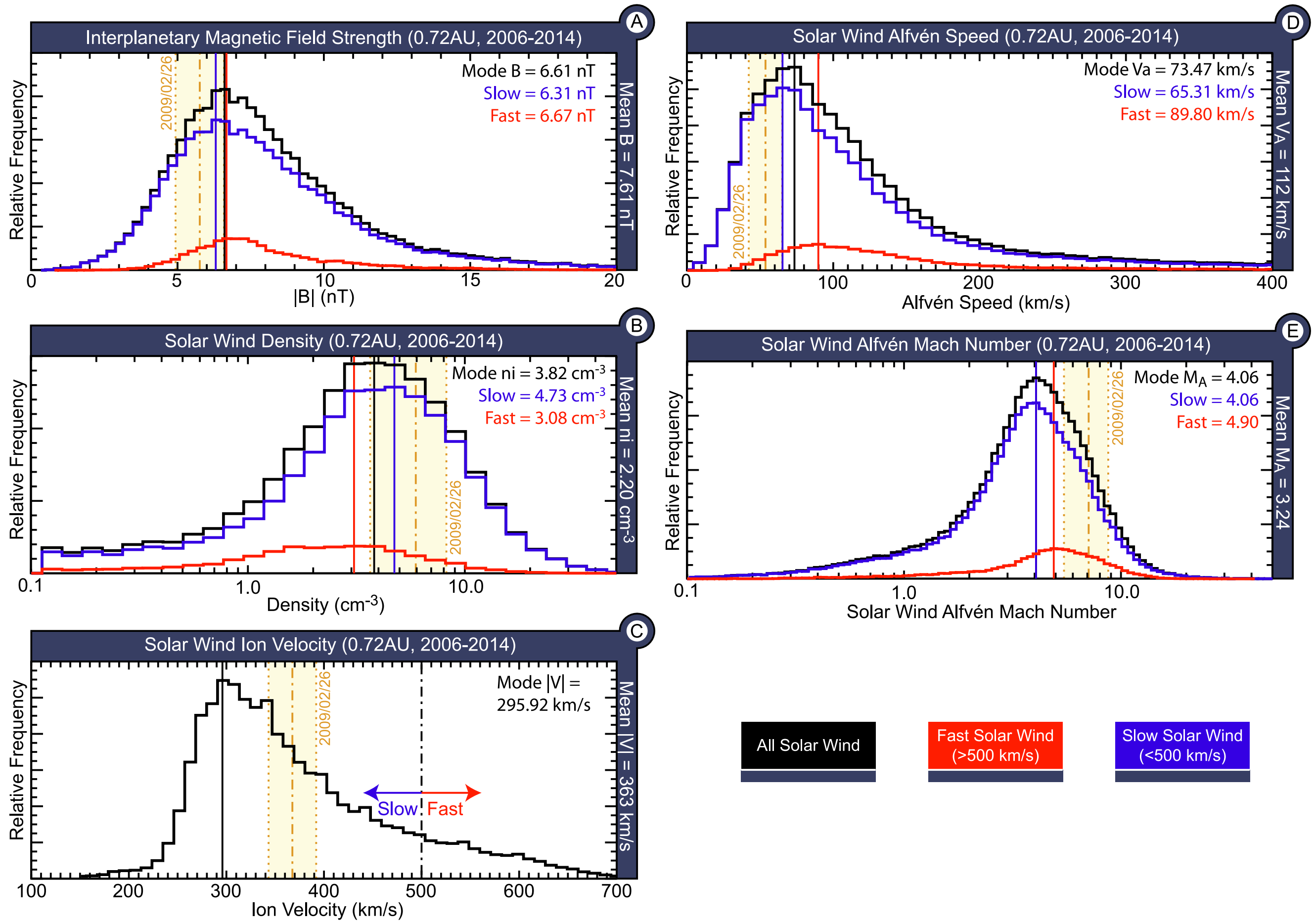

Figure 3. Histograms of properties of the interplanetary magnetic field and solar wind upstream of Venus as measured by the *Venus Express* between 2006 and 2014. Panel A shows the strength of the IMF (|*B*|) from MAG. Panels B and C show solar wind proton density and velocity from ASPERA-4 IMA. Panels D and E show the Alfvén speed and Alfvén Mach Number (as measured, M_A) computed from these properties. Light yellow shading on each panel shows the conditions on 26 February 2009 (this study). Modal averages for each parameter are printed top right of each Panel, and the Mean value for each parameter is printed in the border.

"fast" solar wind (with bulk velocities ≥500 km s^{-1}) (Collinson, Chen, et al., 2022; Stakhiv et al., 2015). Using the strength of the interplanetary magnetic field (|*B*|), solar wind mass density (n_i, calculated using only proton solar wind data from IMA), and velocity (|*V*|), we can compute the Alfvén speed (V_A) and the Alfvén Mach Number (M_A) according to Equation 1.

$$M_A \equiv |V| \left(\frac{4\pi n_i}{|B|^2} \right)^{1/2} \tag{1}$$

Before we discuss M_A during SLAMS observation, we note that our analysis reveals that ASPERA-4 IMA substantially underestimated solar wind n_i. As shown in Figure 3b, the mean solar wind n_i reported by ASPERA-4 IMA at 0.72 AU was 2.2 cm^{-3}, and the mode was 3.8 cm^{-3}, much lower than the expected value of ≈12 cm^{-3} (Köhnlein, 1996). We posit several potential contributing factors to this: (a) All "top hat" analyzers (such as ASPERA-4 IMA) can struggle to accurately measure the absolute densities of quasi-monoenergetic plasma beams such as the solar wind. (b) The field of view of ASPERA-4 IMA was frequently obscured by a thruster; (c) ASPERA-IMA was designed to measure diffuse low energy oxygen ions escaping down the Martian and Venusian magnetotails, and would thus sometimes saturate in the high-flux beam of the solar wind.

Assuming that the mean density was in reality closer to the expected value of ≈12 cm^{-3} and that this error is a linear systematic bias, then we can multiply the n_i measured by ASPERA-4 IMA by ≈×3.1 to make a rough estimate of the actual density $\left(n_i^*\right)$. As per Equation 1, this suggests ASPERA-4 IMA also underestimated the Alfvén Mach number by a factor of ≈×1.77. However, we caution that given the multiple possible contributing factors to the underestimation of solar wind density by ASPERA-IMA (particularly detector saturation), the true bias is unlikely to be this linear and simple.

With this caveat, we find that M_A was unusually high on 26 February 2009, with a mean of 7.10 (measured), in the top 14% of the distribution of all measurements of M_A by the *Venus Express* (Figure 3e), and with an actual value possibly closer to $M_A^* \approx 12.5$. Likewise, when we computed M_A for 11 April 2009 (e.g., conditions during the Collinson, Wilson, et al. (2012) SLAMS case study) we find a similarly high mach number of 7.17, which is in the top 12% of the distribution of all measurements of M_A by the *Venus Express* (Figure 3e), with an estimated actual value of $M_A^* \approx 12.7$.

To investigate whether this apparent dependence on SLAMS/Shocklet formation on high M_A is significant, we ran a one-way analysis of the variance (ANOVA) test on the following two data sets: (a) Solar wind M_A on the 2 days where SLAMS have so far been identified; (b) M_A from the entire mission (Figure 3e). The probability of measuring such high M_A on both days by random chance (The "*P*-value") is 1.2×10^{-4}, that is, very small. We thus show that M_A on these 2 days were statistical outliers at Venus.

This suggests that solar wind Alfvén mach number is likely important for SLAMS (and Shocklet) formation at Venus. This is generally in-line with what is expected from Earth where SLAMS and Shocklets tend to be associated with a higher M_A (Burgess & Scholer, 2013). However, these observations may suggest that the M_A apparently required for their formation at Venus may be exceptionally high for 0.72AU (upper limit of $M_A^* \lesssim 12.5$), corresponding to a lower limit on occurrence rate of ≳14% of the time. This strongly motivates further statistical analysis to more thoroughly establish their occurrence rate at Venus, and their dependence on solar wind Alfvén mach number.

7. Summary and Discussion

In this paper we report the first observation of Shocklets at Venus, and demonstrate that SLAMS can form in the steady-state quasi-parallel Venusian foreshock, despite the magnetosphere being 1/10th smaller than at Earth. Thus we presume one would need to go to an even smaller system to determine the limit in scale-size below which such steepened foreshock structures do not have sufficient time to form.

1. Both SLAMS and Shocklet candidates were observed in the quasi-parallel foreshock, the region where they are found at Earth.
2. MVA analysis revealed that all candidates propagated obliquely to the ambient field with $\theta_{\hat{\mathbf{k}}\langle,\hat{\mathbf{b}}\rangle}$ between 58.6° and 89.27°, consistent with SLAMS and Shocklets (Mann et al., 1994).
3. Two events exhibited the following characteristics consistent with Shocklets.
    (a) They were of classic "sawtooth" appearance with a steeper upstream (trailing) edge (Hoppe & Russell, 1981).

   (b) They were found in the field of 30 s ULF waves, and appear to have replaced two wave crests, suggesting they have steepened directly out of 30 s waves.
   (c) Both candidates exhibited compression ratios (dB/B_0) of 1.3, consistent with Shocklets (higher than 1 but less than 2 (L. B. Wilson et al., 2013)).
   (d) Both candidates were linearly polarized in the spacecraft frame.
4. Three events exhibited the following characteristics consistent with SLAMS.
   (a) Presented as large-amplitude monolithic spikes in $|B|$ that have compression ratios (dB/B_0) between 3.2 $\Rightarrow$ 4.0, with an average of 3.7, consistent with terrestrial SLAMS which have $dB/B_0 \geq 2$ above the background field (Mann et al., 1994; Schwartz et al., 1992).
   (b) Two events were elliptically left-hand polarized in the spacecraft frame consistent with previous observations (Lucek et al., 2004, 2008).

We additionally demonstrated for the first time plasma perturbations associated with Venusian SLAMS and Shocklets. We expect such fast magnetosonic mode structures to be highly compressional, and increasing both $|B|$ and plasma density in phase with each other. We found electron flux to unambiguously increase with $|B|$, consistent with what is expected during both SLAMS and Shocklets.

Through statistical analysis of all solar wind measurements by ESA's *Venus Express* we found that solar wind Alfvén Mach number (M_A) was unusually high both for the SLAMS discovered in this study and those found by Collinson, Wilson, et al. (2012). Our results strongly suggest that high solar wind mach number is a driver of SLAMS formation at Venus. More than 2 events are required to establish a true occurrence rate. However, if we assume that the mach number for this event $\left(M_A^* = 12.5\right)$ is the lower limit, this corresponds to a lower limit on the occurrence rate of $\gtrsim$14% of the time. As solar wind mach number generally increases with distance from the sun, we posit this suggests that SLAMS may be more common at foreshocks at greater Heliospheric distances. Conversely, SLAMS and Shocklets may be less common the closer a planet orbits a star. However, we acknowledge there are significant uncertainties in these numerical estimations, and further analysis is needed to more thoroughly establish an occurrence rate.

Our analysis reveals ASPERA-4 IMA substantially underestimated ion density (n_i) in the solar wind by a factor of $\approx\times3.1$, and thus future users of this data set should be cautious when using the absolute densities it apparently measured, as these may be an underestimation.

Steepened foreshock wave structures (similar to SLAMS) have been shown to directly impact the upper ionosphere of Mars (Collinson et al., 2018; Fowler et al., 2018), and a similar process has been suggested at Venus (Collinson et al., 2020). Thus further exploration of the Venusian foreshock is necessary to (a) understand the occurrence rate of SLAMS and Shocklets; (b) understand how they perturb space near Venus; and (c) how their impact on the ionopause affects the unshielded ionosphere below.

Acknowledgments
G.A.C. and R.F. were supported by a grant from the NASA ROSES Solar System Workings program (Grant 80NSSC20K0317). H.H. is supported by the Royal Society University Research Fellowship URF/R1/180671. M.A. was supported by UKRI (STFC/EPSRC) Stephen Hawking Fellowship EP/T01735X/1. D.M.L. is grateful to the Science Technology and Facilities Council for the award of an Ernest Rutherford Fellowship (ST/R003246/1). This research was supported by the International Space Science Institute (ISSI) in Bern, through ISSI International Team project 465 “Foreshocks Across The Heliosphere: System Specific Or Universal Physical Processes?.” We acknowledge and thank the front-line healthcare workers of our respective countries for their service during the COVID-19 pandemic, the beginning of which coincided with the initiation of this study.

Data Availability Statement

Venus Express Ephemeris data and calibrated ASPERA-ELS data can be found by typing “Venus Express [mission]” into the search bar at the European Space Agency Planetary Science Archive (PSA) (https://archives.esac.esa.int/psa).

References

Andrés, N., Gómez, D. O., Bertucci, C., Mazelle, C., & Dougherty, M. K. (2013). Saturn’s ULF wave foreshock boundary: Cassini observations. *Planetary and Space Science*, *79*, 64–75. https://doi.org/10.1016/j.pss.2013.01.014

Barabash, S., Sauvaud, J.-A., Gunell, H., Andersson, H., Grigoriev, A., Brinkfeldt, K., et al. (2007). The Analyser of Space Plasmas and Energetic Atoms (ASPERA-4) for the Venus Express mission. *Planetary and Space Science*, *55*(12), 1772–1792. https://doi.org/10.1016/j.pss.2007.01.014

Bebesi, Z., Erdos, G., & Szego, K. (2019). Observations of short large amplitude magnetic structures at the Kronian bow shock. *Icarus*, *333*, 306–317. https://doi.org/10.1016/j.icarus.2019.06.023

Behlke, R., André, M., Buchert, S. C., Vaivads, A., Eriksson, A. I., Lucek, E. A., & Balogh, A. (2003). Multi-point electric field measurements of Short Large-Amplitude Magnetic Structures (SLAMS) at the Earth’s quasi-parallel bow shock. *Geophysical Research Letters*, *30*(4), 040000–040001. https://doi.org/10.1029/2002gl015871

Bertucci, C., Achilleos, N., Mazelle, C., Hospodarsky, G. B., Thomsen, M., Dougherty, M. K., & Kurth, W. (2007). Low-frequency waves in the foreshock of Saturn: First results from Cassini. *Journal of Geophysical Research*, *112*(A9), A09219. https://doi.org/10.1029/2006JA012098

Bertucci, C., Duru, F., Edberg, N., Fraenz, M., Martinecz, C., Szego, K., & Vaisberg, O. (2011). The induced magnetospheres of Mars, Venus, and Titan. *Space Science Reviews*, *162*(1–4), 113–171. https://doi.org/10.1007/s11214-011-9845-1

Burgess, D., & Scholer, M. (2013). Microphysics of quasi-parallel shocks in collisionless plasmas. *Space Science Reviews*, *178*(2–4), 513–533. https://doi.org/10.1007/s11214-013-9969-6

Chen, L.-J., Wang, S., Ng, J., Bessho, N., Tang, J.-M., Fung, S. F., et al. (2021). Solitary magnetic structures at quasi-parallel collisionless shocks: Formation. *Geophysical Research Letters*, *48*(1), e90800. https://doi.org/10.1029/2020GL090800

Collinson, G. A., Chen, L.-J., Jian, L. K., & Dorelli, J. (2022). The solar wind at (16) Psyche: Predictions for a metal world. *The Astrophysical Journal*, *927*(2), 202. https://doi.org/10.3847/1538-4357/ac51d7

Collinson, G. A., Fedorov, A., Futaana, Y., Masunaga, K., Hartle, R., Stenberg, G., et al. (2014). The extension of ionospheric holes into the tail of Venus. *Journal of Geophysical Research: Space Physics*, *119*(8), 6940–6953. https://doi.org/10.1002/2014JA019851

Collinson, G. A., Grebowsky, J., Sibeck, D. G., Jian, L. K., Boardsen, S., Espley, J., et al. (2015). The impact of a slow interplanetary coronal mass ejection (ICME) on Venus. *Journal of Geophysical Research: Space Physics*, *120*(5), 3489–3502. https://doi.org/10.1002/2014JA020616

Collinson, G. A., Kataria, D. O., Coates, A. J., Tsang, S. M. E., Arridge, C. S., Lewis, G. R., et al. (2009). Electron optical study of the Venus Express ASPERA-4 Electron Spectrometer (ELS) top-hat electrostatic analyser. *Measurement Science and Technology*, *20*(5), 055204. https://doi.org/10.1088/0957-0233/20/5/055204

Collinson, G. A., Ramstad, R., Frahm, R., Wilson, L., Xu, S., Whittlesey, P., et al. (2022). A revised understanding of the structure of the Venusian magnetotail from a high-altitude intercept with a tail ray by Parker Solar Probe. *Geophysical Research Letters*, *49*(1), e96485. https://doi.org/10.1029/2021GL096485

Collinson, G. A., Sibeck, D. G., Masters, A., Shane, N., Zhang, T. L., Fedorov, A., et al. (2014). A survey of hot flow anomalies at Venus. *Journal of Geophysical Research: Space Physics*, *119*(2), 978–991. https://doi.org/10.1002/2013JA018863

Collinson, G. A., Sibeck, D., Omidi, N., Frahm, R., Zhang, T., Mitchell, D., et al. (2020). Foreshock cavities at Venus and Mars. *Journal of Geophysical Research: Space Physics*, *125*(8), e28023. https://doi.org/10.1029/2020JA028023

Collinson, G. A., Sibeck, D., Omidi, N., Grebowsky, J., Halekas, J., Mitchell, D., et al. (2017). Spontaneous hot flow anomalies at Mars and Venus. *Journal of Geophysical Research: Space Physics*, *122*(10), 9910–9923. https://doi.org/10.1002/2017JA024196

Collinson, G. A., Sibeck, D. G., Masters, A., Shane, N., Slavin, J. A., Coates, A. J., et al. (2012). Hot flow anomalies at Venus. *Journal of Geophysical Research: Space Physics*, *117*(A16), 4204. https://doi.org/10.1029/2011ja017277

Collinson, G. A., Wilson, L. B., Omidi, N., Sibeck, D., Espley, J., Fowler, C. M., et al. (2018). Solar wind induced waves in the skies of Mars: Ionospheric compression, energization, and escape resulting from the impact of ultralow frequency magnetosonic waves generated upstream of the Martian Bow Shock. *Journal of Geophysical Research: Space Physics*, *123*(9), 7241–7256. https://doi.org/10.1029/2018JA025414

Collinson, G. A., Wilson, L. B., III., Sibeck, D. G., Shane, N., Zhang, T. L., Moore, T. E., et al. (2012). Short large-amplitude magnetic structures (SLAMS) at Venus. *Journal of Geophysical Research: Space Physics*, *117*(A16), 10221. https://doi.org/10.1029/2012ja017838

Delva, M., Bertucci, C., Volwerk, M., Lundin, R., Mazelle, C., & Romanelli, N. (2015). Upstream proton cyclotron waves at Venus near solar maximum. *Journal of Geophysical Research: Space Physics*, *120*(1), 344–354. https://doi.org/10.1002/2014JA020318

Dorfman, S., Hietala, H., Astfalk, P., & Angelopoulos, V. (2017). Growth rate measurement of ULF waves in the ion foreshock. *Geophysical Research Letters*, *44*(5), 2120–2128. https://doi.org/10.1002/2017GL072692

Dubinin, E., & Fraenz, M. (2016). *Ultra-low-frequency waves at Venus and Mars* (Vol. 216, pp. 343–364). Washington DC American Geophysical Union Geophysical Monograph Series. https://doi.org/10.1002/9781119055006.ch20

Dubinin, E., Fraenz, M., Woch, J., Zhang, T. L., Wei, Y., Fedorov, A., et al. (2013). Toroidal and poloidal magnetic fields at Venus. Venus Express observations. *Planetary and Space Science*, *87*, 19–29. https://doi.org/10.1016/j.pss.2012.12.003

Dubouloz, N., & Scholer, M. (1993). On the origin of short large-amplitude magnetic structures upstream of quasi-parallel collisionless shocks. *Geophysical Research Letters*, *20*(7), 547–550. https://doi.org/10.1029/93gl00803

Eastwood, J. P., Balogh, A., Lucek, E. A., Mazelle, C., & Dandouras, I. (2005). Quasi-monochromatic ULF foreshock waves as observed by the four-spacecraft cluster mission: 2. Oblique propagation. *Journal of Geophysical Research*, *110*(A9), 11220. https://doi.org/10.1029/2004ja010618

Eastwood, J. P., Lucek, E. A., Mazelle, C., Meziane, K., Narita, Y., Pickett, J., & Treumann, R. A. (2005). The foreshock. *Space Science Reviews*, *118*(1–4), 41–94. https://doi.org/10.1007/s11214-005-3824-3

Fairfield, D. H. (1969). Bow shock associated waves observed in the far upstream interplanetary medium. *Journal of Geophysical Research*, *74*(14), 3541–3553. https://doi.org/10.1029/ja074i014p03541

Fairfield, D. H. (1971). Average and unusual locations for the earth's magnetopause and bow shock. *Journal of Geophysical Research*, *76*(28), 6700–6716. https://doi.org/10.1029/ja076i028p06700

Fowler, C. M., Andersson, L., Ergun, R. E., Harada, Y., Hara, T., Collinson, G., et al. (2018). MAVEN observations of solar wind-driven magnetosonic waves heating the Martian dayside ionosphere. *Journal of Geophysical Research: Space Physics*, *123*(5), 4129–4149. https://doi.org/10.1029/2018JA025208

Fränz, M., Echer, E., Marques de Souza, A., Dubinin, E., & Zhang, T. L. (2017). Ultra low frequency waves at Venus: Observations by the Venus express spacecraft. *Planetary and Space Science*, *146*, 55–65. https://doi.org/10.1016/j.pss.2017.08.011

Futaana, Y., Stenberg Wieser, G., Barabash, S., & Luhmann, J. G. (2017). Solar wind interaction and impact on the Venus atmosphere. *Space Science Reviews*, *212*(3–4), 1453–1509. https://doi.org/10.1007/s11214-017-0362-8

Greenstadt, E. W., Baum, L. W., Jordan, K. F., & Russell, C. T. (1987). The compressional ULF foreshock boundary of Venus: Observations by the PVO magnetometer. *Journal of Geophysical Research*, *92*(A4), 3380–3384. https://doi.org/10.1029/JA092iA04p03380

Gurnett, D. A., & Bhattacharjee, A. (2005). *Introduction to plasma physics*. Cambridge University Press.

Halekas, J. S., Ruhunusiri, S., Harada, Y., Collinson, G., Mitchell, D. L., Mazelle, C., et al. (2017). Structure, dynamics, and seasonal variability of the Mars-solar wind interaction: MAVEN solar wind ion analyzer in-flight performance and science results. *Journal of Geophysical Research: Space Physics*, *122*(1), 547–578. https://doi.org/10.1002/2016JA023167

Hoppe, M., & Russell, C. (1981). On the nature of ULF waves upstream of planetary bow shocks. *Advances in Space Research*, *1*(1), 327–332. https://doi.org/10.1016/0273-1177(81)90129-0

Köhnlein, W. (1996). Radial dependence of solar wind parameters in the ecliptic (1.1 R ⊙-61 AU). *Solar Physics*, *169*(1), 209–213. https://doi.org/10.1007/BF00153841

Lucek, E. A., Horbury, T. S., Balogh, A., Dandouras, I., & Rème, H. (2004). Cluster observations of hot flow anomalies. *Journal of Geophysical Research: Space Physics*, *109*(A18), A06207. https://doi.org/10.1029/2003ja010016

Lucek, E. A., Horbury, T. S., Dandouras, I., & Rème, H. (2008). Cluster observations of the Earth's quasi-parallel bow shock. *Journal of Geophysical Research: Space Physics*, *113*(A12), 7. https://doi.org/10.1029/2007ja012756

Luhmann, J. G. (1990). The solar wind interaction with unmagnetized planets—A tutorial. *Geophysical Monograph Series*, *58*, 401–411. https://doi.org/10.1029/GM058p0401

Luhmann, J. G., Russell, C. T., & Elphic, R. (1986). Spatial distributions of magnetic field fluctuations in the dayside magnetosheath. *Journal of Geophysical Research*, *91*(A2), 1711–1715. https://doi.org/10.1029/ja091ia02p01711

Luhmann, J. G., Russell, C. T., Phillips, J. L., & Barnes, A. (1987). On the role of the quasi-parallel bow shock in ion pickup—A lesson from Venus? *Journal of Geophysical Research*, *92*(A3), 2544–2550. https://doi.org/10.1029/ja092ia03p02544

Mann, G., Luehr, H., & Baumjohann, W. (1994). Statistical analysis of short large-amplitude magnetic field structures in the vicinity of the quasi-parallel bow shock. *Journal of Geophysical Research*, *99*(A7), 13315. https://doi.org/10.1029/94ja00440

Omidi, N., Collinson, G., & Sibeck, D. (2017). Structure and properties of the foreshock at Venus. *Journal of Geophysical Research: Space Physics*, *122*(10), 10275–10286. https://doi.org/10.1002/2017JA024180

Omidi, N., Collinson, G., & Sibeck, D. (2020). Foreshock Bubbles at Venus: Hybrid simulations and VEX observations. *Journal of Geophysical Research: Space Physics*, *125*(2), e27056. https://doi.org/10.1029/2019JA027056

Orlowski, D. S., Crawford, G. K., & Russell, C. T. (1990). Upstream waves at Mercury, Venus and Earth—omparison of the properties of one Hertz waves. *Geophysical Research Letters*, *17*(13), 2293–2296. https://doi.org/10.1029/GL017i013p02293

Scarf, F. L., Fredricks, R. W., Frank, L. A., Russell, C. T., Coleman, P. J., Jr., & Neugebauer, M. (1970). Direct correlations of large-amplitude waves with suprathermal protons in the upstream solar wind. *Journal of Geophysical Research*, *75*(34), 7316–7322. https://doi.org/10.1029/ja075i034p07316

Schwartz, S. J. (1991). Magnetic field structures and related phenomena at quasi-parallel shocks. *Advances in Space Research*, *11*(9), 231–240. https://doi.org/10.1016/0273-1177(91)90039-m

Schwartz, S. J., Burgess, D., Wilkinson, W. P., Kessel, R. L., Dunlop, M., & Luehr, H. (1992). Observations of short large-amplitude magnetic structures at a quasi-parallel shock. *Journal of Geophysical Research*, *97*(A4), 4209–4227. https://doi.org/10.1029/91ja02581

Shan, L., Lu, Q., Wu, M., Gao, X., Huang, C., Zhang, T., & Wang, S. (2014). Transmission of large-amplitude ULF waves through a quasi-parallel shock at Venus. *Journal of Geophysical Research: Space Physics*, *119*(1), 237–245. https://doi.org/10.1002/2013JA019396

Shan, L., Mazelle, C., Meziane, K., Romanelli, N., Ge, Y. S., Du, A., et al. (2018). The quasi-monochromatic ULF wave boundary in the Venusian foreshock: Venus Express observations. *Journal of Geophysical Research: Space Physics*, *123*(1), 374–384. https://doi.org/10.1002/2017JA024054

Shuvalov, S. D., & Grigorenko, E. E. (2023). Observation of slams-like structures close to Martian aphelion by MAVEN. *Journal of Geophysical Research: Space Physics*, *128*(5), e2022JA031018. https://doi.org/10.1029/2022ja031018

Slavin, J. A., Elphic, R. C., Russell, C. T., Scarf, F. L., Wolfe, J. H., Mihalov, J. D., et al. (1980). The solar wind interaction with Venus - Pioneer Venus observations of bow shock location and structure. *Journal of Geophysical Research*, *85*(A13), 7625–7641. https://doi.org/10.1029/ja085ia13p07625

Smith, E. J., Davis, L., Jr., Coleman, P. J., Jr., & Sonett, C. P. (1965). Magnetic measurements near Venus. *Journal of Geophysical Research*, *70*(7), 1571–1586. https://doi.org/10.1029/jz070i007p01571

Sönnerup, B., & Scheible, M. (1998). *Analysis methods for multi-spacecraft data*. In G. Paschmann & P. W. Daly (Eds.), (Vol. 1, chap. 8). ISSI Scientific Reports Series SR-001.

Stakhiv, M., Landi, E., Lepri, S. T., Oran, R., & Zurbuchen, T. H. (2015). On the origin of Mid-latitude fast wind: Challenging the two-state solar wind paradigm. *The Astrophysical Journal*, *801*(2), 100. https://doi.org/10.1088/0004-637X/801/2/100

Takahashi, K., McPherron, R. L., & Hughes, W. J. (1984). Multispacecraft observations of the harmonic structure of Pc 3-4 magnetic pulsations. *Journal of Geophysical Research*, *89*(A8), 6758–6774. https://doi.org/10.1029/JA089iA08p06758

Thomsen, M. F., Thomas, V. A., Winske, D., Gosling, J. T., Farris, M. H., & Russell, C. T. (1993). Observational test of hot flow anomaly formation by the interaction of a magnetic discontinuity with the bow shock. *Journal of Geophysical Research*, *98*(A9), 15319. https://doi.org/10.1029/93JA00792

Tsubouchi, K., & Lembège, B. (2004). Full particle simulations of short large-amplitude magnetic structures (SLAMS) in quasi-parallel shocks. *Journal of Geophysical Research: Space Physics*, *109*(A18), 2114. https://doi.org/10.1029/2003ja010014

Tsurutani, B. T., Arballo, J. K., Smith, E. J., Southwood, D., & Balogh, A. (1993). Large-amplitude magnetic pulses downstream of the Jovian bow shock: Ulysses observations. *Planetary and Space Science*, *41*(11–12), 851–856. https://doi.org/10.1016/0032-0633(93)90092-g

Tsurutani, B. T., Smith, E. J., Thorne, R. M., Gosling, J. T., & Matsumoto, H. (1987). Steepened magnetosonic waves at Comet Giacobini-Zinner. *Journal of Geophysical Research*, *92*(A10), 11074–11082. https://doi.org/10.1029/ja092ia10p11074

Wilson, L. B., III., Cattell, C. A., Kellogg, P. J., Goetz, K., Kersten, K., Kasper, J. C., et al. (2009). Low-frequency whistler waves and shocklets observed at quasi-perpendicular interplanetary shocks. *Journal of Geophysical Research*, *114*(A13), 10106. https://doi.org/10.1029/2009ja014376

Wilson, L. B., Koval, A., Sibeck, D. G., Szabo, A., Cattell, C. A., Kasper, J. C., et al. (2013). Shocklets, SLAMS, and field-aligned ion beams in the terrestrial foreshock. *Journal of Geophysical Research: Space Physics*, *118*(3), 957–966. https://doi.org/10.1029/2012JA018186

Zhang, T. L., Baumjohann, W., Delva, M., Auster, H.-U., Balogh, A., Russell, C. T., et al. (2006). Magnetic field investigation of the Venus plasma environment: Expected new results from Venus Express. *Planetary and Space Science*, *54*(13–14), 1336–1343. https://doi.org/10.1016/j.pss.2006.04.018