Short Large-Amplitude Magnetic Structures (SLAMS) at Venus

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Abstract.

We present the first observation of magnetic fluctuations consistent with Short Large-Amplitude Magnetic Structures (SLAMS) in the foreshock of the planet Venus. Three monolithic magnetic field spikes were observed by the *Venus Express* on the 11th of April 2009. The structures were $\sim$1.5$\rightarrow$11s in duration, had magnetic compression ratios between $\sim$3$\rightarrow$6, and exhibited elliptical polarization. These characteristics are consistent with the SLAMS observed at Earth, Jupiter, and Comet Giacobini-Zinner, and thus we hypothesize that it is possible SLAMS may be found at any celestial body with a foreshock.

1. Introduction

The foreshock is the region of space upstream from a celestial body which is magnetically connected to the bow shock [*Eastwood et al.*, 2005]. It is pervaded by a field of ULF waves [*Fairfield*, 1969; *Scarf et al.*, 1970] which are thought to be driven by field-aligned ion beams reflected at the bow shock [*Tsurutani and Rodriguez*, 1981; *Hoppe and Russell*, 1983], or produced locally [*Hellinger and Mangeney*, 1999; *Mazelle et al.*, 2003; *Meziane et al.*, 2004]. ULF waves have been observed at many planets including Venus [*Hoppe and Russell*, 1981], Jupiter [*Tsurutani et al.*, 1993b], and at interplanetary shocks [*Tsurutani et al.*, 1983]. The waves attempt to propagate upstream, but are convected back toward the bow shock by the solar wind. As they convect deeper into the foreshock, they enter regions of higher diffuse ion density. These ions alter the index of refraction for the medium causing transverse modes to become compressive, and thus the waves can steepen [e.g. *Wilson et al.*, 2009; *Tsubouchi and Lembège*, 2004; *Tsurutani et al.*, 1987, and references therein]. They become more oblique and compressional the deeper they go.

One of the possible resulting foreshock phenomena are Short Large-Amplitude Magnetic Structures (SLAMS), pulsations believed to steepen out of the background ULF wave field due to the interaction with diffuse ions [e.g. *Scholer et al.*, 2003; *Dubouloz and Scholer*, 1995]. As the waves convected back toward the bow shock, the different wave fronts (i.e. wave crests and troughs) cause a differential slowing of the incident solar wind flow which leads to the refraction of the waves. As the amplitude of the SLAMS increases, their phase speed also increases. *Dubouloz and Scholer* [1995] found that SLAMS are left hand polarized in the plasma frame, that both upstream and downstream edges steepen, and that some pulsations appear to nearly stand against the incident flow. SLAMS are distributed over a transition region of 2-3 R_E, with individual scale sizes of ~700→1000km, or ~10→15 ion inertial lengths.

SLAMS are elliptically polarized and compressive characterized by brief $(5-20s)$ monolithic spikes in magnetic field magnitude ($|B|$), with compression ratio ($\delta B/B_0$) between 2 to 5 times the background field [*Schwartz*, 1991; *Tsurutani et al.*, 1993a; *Schwartz et al.*, 1992; *Dubouloz and Scholer*, 1993]. They are commonly observed in the quasi-parallel (i.e. where the angle between the magnetic field vector and the normal to the bow shock, $\theta_{Bn} < 45°$) foreshock when and where the Interplanetary Magnetic Field (IMF) lies quasi-parallel to the bow shock normal [*Schwartz*, 1991].

As SLAMS convect Earthwards, their phase speed increases as their amplitude increases [*Omidi and Winske*, 1990]. Thus their motion relative to the planet decreases, and they coalese together to form the complex three-dimensional patchwork of the quasi-parallel shock [*Schwartz and Burgess*, 1991; *Lucek et al.*, 2008] (although not all observations of quasi-parallel shocks are thought to obey this paradigm [*Burgess*, 1995]). Thus, understanding SLAMS is crucial to understanding how the Earth's shock forms under certain IMF conditions.

The first extra-terrestrial observation of *"steepened magnetosonic waves"* consistent with SLAMS was made by *Tsurutani et al.* [1990] at Comet Giacobini-Zinner. The pulses exhibited compression ratios ($\delta B/B_0$) of 2.3 to 7.0, had full-width half-maximum durations from 12 to 72s, comparable to the H_2O group ion gyroperiod (67s in a 15nT field), and were circularly polarized with right-hand rotation in the spacecraft frame. Later *Tsurutani et al.* [1993a, b] reported the discovery of large-amplitude magnetic pulses upstream of the Jovian bow shock by *Ulysses*. The magnetic pulses they reported were similar to SLAMS in that they were planar elliptically polarized structures, although their peak amplitudes were lower ($0.5 \rightarrow 2\,|B_0|$) than typically observed at the Earth, and the duration of the pulses was much longer (∼1 minute).

In this paper we present the first observations of magnetic pulsations consistent with SLAMS in the Cytherean foreshock by the ESA *Venus Express* [*Svedhem et al.*, 2007] magnetometer [*Zhang et al.*, 2006]. We also present supplementary data from the Analyser of Space Plasmas and Energetic Atoms (ASPERA) Electron Spectrometer (ELS) [*Barabash et al.*, 2007], although direct measurement of the plasma properties of the SLAMS were not possible due to limits in the temporal resolution, and low sensitivity [*Collinson et al.*, 2009] owing to a reduced geometric factor [*Collinson et al.*, 2012b] of ASPERA-ELS.

Our paper is outlined as follows: In section 2 we present a global overview of the Cytherean foreshock encounter by the *Venus Express* on the 11th of April 2009; In section 3.1 we present observations of the ∼2 minute period in which three SLAMS were observed; In section 3.3 we present an example of our analysis of the magnetic field data from an ∼11 second period containing three SLAMS; and in section 4 we summarize our findings and compare the Cytherean SLAMS with their Terrestrial, Jovian, and Cometary counterparts.

2. Overview of Cytherean upstream conditions on the 11th of April 2009

In this section we present data from the ~12 minute period that begins in the distant foreshock region where magnetic fluctuations consistent with SLAMS were observed, continues through the three bow shock crossings observed that day, and ends when the *Venus Express* goes into the magnetosheath for the third and final time. This global overview puts our later description of Cytherean SLAMS into context.

2.1. Review of Cytherean induced magnetosphere

Although Venus has no intrinsic magnetic field [*Smith et al.*, 1965], its conductive ionosphere creates an impassable barrier to the IMF [*Zhang et al.*, 1991]. Magnetic field lines frozen into the solar wind flow collide with the planetary ionosphere and pile up on the day-side, resulting in the generation of an induced magnetosphere [*Zhang et al.*, 2008]. This induced magnetic field is an obstacle to the supersonic solar wind and thus a supersonic bow shock is generated [*Ness et al.*, 1974; *Russell et al.*, 1979]. The stand-off distance of the Cytherean bow shock is much less than that at the Earth, with a closest altitude of ~1.5 Venus Radii (R_V) [*Slavin et al.*, 1980], as compared to $\approx 15\, R_E$ [*Fairfield*, 1971]. The *Venus Express* is in an elliptical quasi-polar orbit with a period of ~24 hours, with an apogee over the south pole of $\approx 12 R_V$ [*Titov et al.*, 2006] and perigee inside the ionosphere over the north pole of $\approx 1.04 R_V$.

2.2. Map of Orbit 1086

Figure 1 shows a map of the relevant orbit (1086) on the 11th of April 2009. Panels A, B, and C show the orbital encounter in Venus Solar Orbital (VSO) coordinates, where x points towards the sun, y points back along the orbital path of the planet, and z points out of the plane of the ecliptic completing the right-hand set. Panel D shows the course of the *Venus Express* in cylindrical coordinates, where the x-axis points towards the sun, and the y-axis represents the radial distance from the planet ($R = \sqrt{(y^2 + z^2)}$). This 2D cylindrical projection allows us to plot the positions of the observed bow shock crossings and SLAMS in relation to the idealised bow shock (black line) of *Slavin et al.* [1980]. The blue line represents the path of the *Venus Express*, the pink circles denote the locations of observed bow shock crossings, the yellow stars denote the location where SLAMS were observed, and the light blue line running parallel to the orbit for a distance between $\sim 2.5 R_V \rightarrow 1.9 R_V$ shows the part of the orbit from which we present data in this section.

As can be seen from Figure 1, *Venus Express* was approaching the planet along the flanks, from a latitude of $\sim 78°$. The position of the Cytherean bow shock is known to be highly variable [*Slavin et al.*, 1980; *Russell et al.*, 1988; *Martinecz et al.*, 2008], and three distinct bow shock crossings were observed on the 11th of April 2009. The furthest crossing was significantly further away from the planet than expected from an idealized hyperbolic model ($2.3 R_V$ vs. $1.8 R_V$).

2.3. Magnetometer and Electron Spectrometer observations

Figure 2 shows magnetometer and ASPERA-ELS measurements from between 02:42:30 and 02:54:30 (The period of the orbit highlighted by the light blue line in Figure 1).

Panel A presents a color-coded timeline showing which of the three regions of space (solar wind, foreshock, magnetosheath) the spacecraft was occupying at any given time. The three bow shock crossings are highlighted with pink circles and vertical dotted lines that have been extended throughout the Figure. The magnetic pulsations which we examine in detail are denoted by yellow stars. The light blue track (in Panel A) running parallel to the timeline from 02:43:00 to 02:45:10 highlights the period of the main event where these magnetic pulsations were observed, and will be covered in more detail in Figure 3 and accompanying Section 3.1.

Panels B through E present the four magnetic field components ($|B|, B_x, B_y, B_z$) in VSO coordinates, respectively. The black line is the full 32 samples per second resolution data and the red line is the same data set averaged at $\frac{1}{4}$ samples per second so that trends can be more easily identified. Panel F shows a plot of the shock normal angle, θ_{Bn}, between an extension of the local magnetic field vector to a model bow shock drawn according to *Slavin et al.* [1980]. Periods when there is no data in panel F indicate when there was no connection between the magnetic field and the model bow shock. Panel G shows an electron spectrogram of the plasma observed by ASPERA-ELS. We have over-plotted $|B|$ (y-axis is arbitrary) to highlight trends between magnetic field magnitude and the electron flux.

There were three encounters with the magnetosheath (marked in pink on the timeline) and associated bow shock crossings (pink circles). The clearest and best example is the final (right most in Figure 2) bow shock crossing at ∼02:53:45, after which the magnetosheath is clearly visible in panel G by an increase in $|B|$, and an increase in flux of electrons over a broad range of energies, consistent with heating at the bow shock [*Pérez-de-Tejada et al.*, 2011]. The two other transitions into the sheath at ∼02:45:00 and ∼02:52:30 were brief, but are evident by the change the orientation of the magnetic field, an increase in $|B|$, and an increase in electron flux consistent with that of the final bow shock crossing. Thus the magnetic pulsations of interest (marked by yellow stars on the timeline, although not yet visible at this scale) were observed shortly before a distant bow shock crossing at ∼02:45:00.

The period preceding the earliest transition into the sheath from ∼02:42:30 until ∼02:45:00 is much more turbulent than the solar wind. There was magnetic connectivity to the bow shock, with (θ_{Bn}) initially near $\sim 60°$, and then fluctuating due to magnetic turbulence. It is very important to recall that these angles are based on an idealised nominal bow shock, and the distant bow shock crossing was $\sim 0.5 R_V$ further away than predicted by this model (see Figure 1). Given that this most distant magnetosheath crossing was very brief ($6.4s$), and that it occurred so far from the nominal bow shock, this suggests that this brief shift in the position of the bow shock was due a reaction to some unknown external solar wind stimuli.

One possible explanation for this outward shift is a Hot Flow Anomaly (HFA) [*Collinson et al.*, 2012b]. HFAs are features that form in close proximity to the bow shock at the intersection of certain interplanetary discontinuities with the bow shock. The brief reductions in pressure associated with HFAs can enable both bow shock and magnetopause to move outward far beyond their mean positions [*Sibeck et al.*, 1999]. HFAs exhibit greatly heated populations of ions and electrons, as well as highly deflected flows. Consistent with this interpretation, our event exhibited electron signatures consistent with heating, and a rotation in the magnetic field. In the absence of high time resolution ion measurements, we cannot comment on any concomitant flow deflections or ion heating. Regardless of the presence or absence of an HFA, the turbulent magnetic field, magnetic connection to the bow shock, and shock-like crossing at ∼02:45:00 suggest that the *Venus Express* was in the foreshock, the region where SLAMS are expected at Earth. We will now take a closer look at the period covered by the light blue parallel track on the timeline (Panel A.) of Figure 2.

3. SLAMS at Venus

3.1. Overview of distant foreshock crossing containing SLAMS

Figure 3 shows the period when we observed the three magnetic fluctuations which we identify as SLAMS. We have highlighted three such fluctuations using a yellow bar and star on the timeline (Panel A) because they also exhibit a brief spike in $|B|$. The periods when the spacecraft was in the foreshock are marked by a purple bar on the timeline, and the brief ∼6s Magnetosheath crossing is marked in pink with associated bow shock crossings marked by pink circles.

3.2. Observed properties of Cytherean SLAMS

The most obvious feature of the three magnetic pulsations highlighted in Figure 3 is the brief monolithic spikes in $|B|$ at ∼02:43:51, ∼44:44, and ∼44:58. The average compression ratio was ∼4 times the background field. The pulsations had durations between

$\sim$1.5 $\rightarrow$ 11 seconds. Additionally, the $(\delta B/B_0)$ of the leading edge of each increases from $\sim$3 $\Rightarrow$ 6, as Venus Express approaches the bow shock (or vice-versa). These magnetic compression ratios are greater than 2, consistent with observations of SLAMS at the Earth [*Mann et al.*, 1994]. The compression ratios of the two later pulsations was greater than the maximum factor of four for simple compression [*Gurnett and Bhattacharjee*, 2005], which is also consistent with observations of SLAMS [*Schwartz et al.*, 1992]. During the pulsations, the magnetic fields rotate from a quasi-parallel orientation to a locally quasi-perpendicular orientation, consistent with observations of SLAMS by *Mann et al.* [1994]. At and near the time of the pulsations there are intervals of nearly quasi-parallel bow shock configurations, although the degree of turbulence is so great that there also disconnections. As a whole, during the time of the events, we believe this to be a quasi-parallel bow shock.

3.3. Minimum variance analysis of Cytherean SLAMS

We performed minimum variance analysis (MVA) on subintervals of the time series using multiple frequency filters to determine the propagation characteristics of the wave. For more details about this technique, see *Wilson et al.* [2009]. This process was performed on the steepened leading (upstream) edge of the magnetic pulsations. Figure 4 shows magnetometer data from the eleven second period (02:43:50 to 02:44:01) showing an example of a Short Large-Amplitude Magnetic Structure (SLAMS) at Venus. Panels A to D show the data in VSO coordinates, where the black line is 32 samples per second resolution, and the red line is the appropriate subinterval of this data with a $0.2 - 1Hz$ filter applied. Panels E and F of Figure 4 show hodograms of this filtered subinterval of magnetic field data. Panel E is in VSO co-ordinates, and Panel F is the same data after MVA. All three of the magnetic structures analyzed were left-hand polarized in the minimum variance direction. However, with only single spacecraft magnetic field observations, we cannot define the correct sign of this vector [*Khrabrov and Sonnerup*, 1998].

The magnetic field was rotated into field-aligned co-ordinates (not shown) to investigate the polarization of the fluctuations with respect to the quasi-static magnetic field. The first structure was highly complex. The leading edge spike (as shown in Figure 4) was both right and left-hand polarized, whereas the trailing edge of the larger structure was left-hand polarized in the spacecraft frame. The second (far shorter) structure was left-hand polarized in the spacecraft frame, and the third structure exhibited both left and right handed components. These results are consistent with simulations [e.g. *Dubouloz and Scholer*, 1995] and previous observations [e.g. *Schwartz et al.*, 1992; *Mann et al.*, 1994] who found that pulsations showed left-hand and right-hand polarization in the simulation (i.e. spacecraft) frame, with left-hand polarization in the plasma frame. However, it is not possible to determine the wave polarization in the spacecraft frame using only magnetic field observations with a single spacecraft.

Panel F shows that the leading (upstream) edge of the structure was elliptically polarized, consistent with previous observations [*Schwartz et al.*, 1992; *Tsurutani et al.*, 1993a; *Dubouloz and Scholer*, 1993]. Note that previous studies have referred to this edge as the "trailing" edge [e.g. *Schwartz et al.*, 1992]. The eigenvalues of the MVA were $(\lambda_{mid}/\lambda_{min}) = 101$, and $(\lambda_{max}/\lambda_{min}) = 1.6$, which shows we have a nearly circularly polarized wave. Our MVA analysis showed an average $\theta_{\hat{\mathbf{k}}.\langle\hat{\mathbf{b}}\rangle} \approx \underline{61.7}^{\circ}$, consistent with previous observations in the terrestrial foreshock [e.g. *Mann et al.*, 1994], and upstream of Comet Giacobini-Zinner [*Tsurutani et al.*, 1990].

4. Summary and Discussion

In this paper we have reported the first observation of Cytherean Short Large-Amplitude Magnetic Structures (SLAMS) by the *Venus Express* Magnetometer. SLAMS are common features of the Earth's foreshock, and can be part of the 3D patchwork of magnetic structures that compose the quasi-parallel bow shock. We believe these magnetic pulsations to be SLAMS because they share the following properties with their terrestrial equivalents:

1. They were observed on interplanetary magnetic field lines connected to the bow shock, i.e. the foreshock, the region where SLAMS are observed at Earth.

2. We observed large-amplitude monolithic spikes in $|B|$ that have compression ratios greater than a factor of 2 above the background field, (($\delta B/B_0$) between $\sim 3 \Rightarrow 6$), with an average of $\sim$4, consistent with previous observations [e.g. *Schwartz et al.*, 1992; *Mann et al.*, 1994].

3. On the whole, the pulsations had higher compression ratios than can be explained by simple compression, consistent with pervious observations [*Schwartz et al.*, 1992].

4. They exhibit left-hand elliptical polarization in the spacecraft frame, consistent with previous observations [*Lucek et al.*, 2004, 2008].

5. MVA analysis of one example revealed that it propagated obliquely to the ambient field with $\theta_{\hat{\mathbf{k}}.\langle\hat{\mathbf{b}}\rangle} \approx 61.7°$, consistent with SLAMS [*Mann et al.*, 1994].

Our findings are consistent with *Tsurutani et al.* [1990], who reported solitary circularly polarized magnetic pulses at comet Giacobini-Zinner, with typical peak-to-background compression ratios of ∼4, with $\theta_{\hat{\mathbf{k}}.\langle\hat{\mathbf{b}}\rangle}$ between 55° to 75°. The durations of the Cytherean SLAMS were consistent with the ∼10s typically reported at the Earth [*Schwartz*, 1991], and shorter than the ∼60s structures observed at Jupiter and 12s ⇒ 72s at the Comet (which *Tsurutani et al.* [1990] reported was comparable to the local H_2O group gyroperiod of 67s in a 15nT field). The duration of the monolithic peaks was ∼1.5s ⇒ 11s, similar to the local proton gyroperiod of 9.4s in a 7nT field.

Our calculation of $\theta_{\hat{\mathbf{k}}.\langle\hat{\mathbf{b}}\rangle} \approx 61.7°$ is consistent with SLAMS acting like a local quasi perpendicular shock, consistent with previous interpretations [*Mann et al.*, 1994]. Compressional waves like this perturb the medium, increasing both $|B|$ and plasma density which are in phase with one another [*Hellinger and Mangeney*, 1999]. However, it is not possible for us to compare any plasma perturbations with those known to occur at terrestrial SLAMS [*Giacalone et al.*, 1993; *Behlke et al.*, 2003; *Dubouloz and Scholer*, 1993] due to the limitations of ASPERA.

Though only three SLAMS were observed, the short period of the compressive leading edges (0.4s ⇒ 0.7s) means that they are only clearly visible in the full 32 sample per second resolution data, and are therefore not evident in browse plots. The three SLAMS presented here were discovered by chance during a survey of Cytherean Hot Flow Anomalies [*Collinson et al.*, 2012a], and further study is needed to determine if SLAMS are a common feature of the Cytherean foreshock, as they are at Earth.

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References

Barabash, S., et al., The Analyser of Space Plasmas and Energetic Atoms (ASPERA-4) for the Venus Express mission, *Planet. Space. Sci.*, *55*, 1772–1792, 2007.

Behlke, R., M. André, S. C. Buchert, A. Vaivads, A. I. Eriksson, E. A. Lucek, and A. Balogh, Multi-point electric field measurements of Short Large-Amplitude Magnetic Structures (SLAMS) at the Earth's quasi-parallel bow shock, *Geophys. Res. Lett.*, *30*(4), 040,000–1, 2003.

Burgess, D., Foreshock-shock interaction at collisionless quasi-parallel shocks, *Advances in Space Research*, *15*, 159–169, 1995.

Collinson, G. A., D. O. Kataria, A. J. Coates, S. M. E. Tsang, C. S. Arridge, G. R. Lewis, R. A. Frahm, J. D. Winningham, and S. Barabash, Electron optical study of the Venus Express ASPERA-4 Electron Spectrometer (ELS) top-hat electrostatic analyser, *Measurement Science and Technology*, *20*(5), 055,204–+, 2009.

Collinson, G. A., et al., The geometric factor of electrostatic plasma analyzers: A case study from the Fast Plasma Investigation for the Magnetospheric Multiscale mission, *Review of Scientific Instruments*, *83*(3), 033,303, 2012a.

Collinson, G. A., et al., Hot Flow Anomalies at Venus, *Journal of Geophysical Research*

(Space Physics), *117*(A16), A04204, 2012b.

Dubouloz, N., and M. Scholer, On the origin of short large-amplitude magnetic structures upstream of quasi-parallel collisionless shocks, *Geophys. Res. Lett.*, *20*, 547–550, 1993.

Dubouloz, N., and M. Scholer, Two-dimensional simulations of magnetic pulsations upstream of the Earth's bow shock, *J. Geophys. Res.*, *100*, 9461–9474, 1995.

Eastwood, J. P., et al., Observations of multiple X-line structure in the Earth's magnetotail current sheet: A Cluster case study, *Geophys. Res. Lett.*, *32*, 11,105, doi: 10.1029/2005GL022509, 2005.

Fairfield, D. H., Bow shock associated waves observed in the far upstream interplanetary medium., *J. Geophys. Res.*, *74*, 3541–3553, 1969.

Fairfield, D. H., Average and unusual locations for the earth's magnetopause and bow shock., *J. Geophys. Res.*, *76*, 6700–6716, 1971.

Giacalone, J., S. J. Schwartz, and D. Burgess, Observations of suprathermal ions in association with SLAMS, *Geophys. Res. Lett.*, *20*, 149–152, 1993.

Gurnett, D. A., and A. Bhattacharjee, *Introduction to Plasma Physics*, Cambridge University Press, 2005.

Hellinger, P., and A. Mangeney, Electromagnetic ion beam instabilities: Oblique pulsations, *J. Geophys. Res.*, *104*, 4669–4680, 1999.

Hoppe, M., and C. Russell, On the nature of ULF waves upstream of planetary bow shocks, *Advances in Space Research*, *1*(1), 327 – 332, 1981.

Hoppe, M. M., and C. T. Russell, Plasma rest frame frequencies and polarizations of the low-frequency upstream waves - ISEE 1 and 2 observations, *J. Geophys. Res.*, *88*, 2021–2027, 1983.

Khrabrov, A. V., and B. U. Ö. Sonnerup, Magnetic variance analysis for small-amplitude waves and flux transfer events on a current sheet, *J. Geophys. Res.*, *103*, 11,907–11,918, 1998.

Lucek, E. A., T. S. Horbury, A. Balogh, I. Dandouras, and H. Rème, Cluster observations of Hot Flow Anomalies, *Journal of Geophysical Research (Space Physics)*, *109*(A18), A06,207, 2004.

Lucek, E. A., T. S. Horbury, I. Dandouras, and H. Rème, Cluster observations of the Earth's quasi-parallel bow shock, *Journal of Geophysical Research (Space Physics)*, *113*(A12), A07S02, 2008.

Mann, G., H. Luehr, and W. Baumjohann, Statistical analysis of short large-amplitude magnetic field structures in the vicinity of the quasi-parallel bow shock, *J. Geophys. Res.*, *99*, 13,315, 1994.

Martinecz, C., et al., Location of the bow shock and ion composition boundaries at Venus Initial determinations from Venus Express ASPERA-4, *Planetary and Space Science*, *56*(6), 780 – 784, 2008.

Mazelle, C., et al., Production of gyrating ions from nonlinear wave-particle interaction upstream from the Earth's bow shock: A case study from Cluster-CIS, *Planet. Space. Sci.*, *51*, 785–795, 2003.

Meziane, K., et al., Bow shock specularly reflected ions in the presence of low-frequency electromagnetic waves: a case study, *Annales Geophysicae*, *22*, 2325–2335, 2004.

Ness, N. F., K. W. Behannon, R. P. Lepping, Y. C. Whang, and K. H. Schatten, Magnetic Field Observations near Venus: Preliminary Results from Mariner 10, *Science*, *183*, 1301–1306, 1974.

Omidi, N., and D. Winske, Steepening of kinetic magnetosonic waves into shocklets - Simulations and consequences for planetary shocks and comets, *J. Geophys. Res.*, *95*, 2281–2300, 1990.

Pérez-de-Tejada, H., R. Lundin, S. Barabash, J. Sauvaud, A. Coates, T. L. Zhang, D. Winningham, M. Reyes-Ruiz, and H. Durand-Manterola, Plasma transition at the flanks of the Venus ionosheath: Evidence from the Venus Express data, *J. Geophys. Res.*, *116*(A15), A01103, 2011.

Russell, C. T., R. C. Elphic, and J. A. Slavin, Initial Pioneer Venus magnetic field results - Dayside observations, *Science*, *203*, 745–748, 1979.

Russell, C. T., E. Chou, J. G. Luhmann, P. Gazis, L. H. Brace, and W. R. Hoegy, Solar and interplanetary control of the location of the Venus bow shock, *J. Geophys. Res.*, *93*, 5461–5469, 1988.

Scarf, F. L., R. W. Fredricks, L. A. Frank, C. T. Russell, P. J. Coleman, Jr., and M. Neugebauer, Direct correlations of large-amplitude waves with suprathermal protons in the upstream solar wind., *J. Geophys. Res.*, *75*, 7316–7322, 1970.

Scholer, M., H. Kucharek, and I. Shinohara, Short large-amplitude magnetic structures and whistler wave precursors in a full-particle quasi-parallel shock simulation, *J. Geophys. Res.*, *108*, 1273, 2003.

Schwartz, S. J., Magnetic field structures and related phenomena at quasi-parallel shocks, *Advances in Space Research*, *11*, 231–240, 1991.

Schwartz, S. J., and D. Burgess, Quasi-parallel shocks - A patchwork of three-dimensional structures, *Geophys. Res. Lett.*, *18*, 373–376, 1991.

Schwartz, S. J., D. Burgess, W. P. Wilkinson, R. L. Kessel, M. Dunlop, and H. Luehr, Observations of short large-amplitude magnetic structures at a quasi-parallel shock, *J. Geophys. Res.*, *97*, 4209–4227, 1992.

Sibeck, D. G., et al., Comprehensive study of the magnetospheric response to a hot flow anomaly, *J. Geophys. Res.,* , *104*, 4577–4594, 1999.

Slavin, J. A., et al., The solar wind interaction with Venus - Pioneer Venus observations of bow shock location and structure, *J. Geophys. Res.,* , *85*, 7625–7641, 1980.

Smith, E. J., L. Davis, Jr., P. J. Coleman, Jr., and C. P. Sonett, Magnetic Measurements near Venus, *J. Geophys. Res.*, *70*, 1571–1586, 1965.

Svedhem, H., et al., Venus Express - The first European mission to Venus, *Planetary and Space Science*, *55*, 1636–1652, 2007.

Titov, D. V., et al., Venus Express science planning, *Planet. Space. Sci.*, *54*, 1279–1297, 2006.

Tsubouchi, K., and B. Lembège, Full particle simulations of short large-amplitude magnetic structures (SLAMS) in quasi-parallel shocks, *Journal of Geophysical Research (Space Physics)*, *109*(A18), A02114, 2004.

Tsurutani, B. T., and P. Rodriguez, Upstream waves and particles: An overview of ISEE results, *J. Geophys. Res.*, *86*, 4319–4324, 1981.

Tsurutani, B. T., E. J. Smith, and D. E. Jones, Waves observed upstream of interplanetary shocks, *J. Geophys. Res.*, *88*, 5645–5656, 1983.

Tsurutani, B. T., E. J. Smith, R. M. Thorne, J. T. Gosling, and H. Matsumoto, Steepened magnetosonic waves at Comet Giacobini-Zinner, *J. Geophys. Res.*, *92*, 11,074–11,082, 1987.

Tsurutani, B. T., E. J. Smith, H. Matsumoto, A. L. Brinca, and N. Omidi, Highly non-linear magnetic pulses at Comet Giacobini-Zinner, *Geophys. Res. Lett.*, *17*, 757–760, 1990.

Tsurutani, B. T., J. K. Arballo, E. J. Smith, D. Southwood, and A. Balogh, Large-amplitude magnetic pulses downstream of the Jovian bow shock: Ulysses observations, *Planet. Space. Sci.*, *41*, 851–856, 1993a.

Tsurutani, B. T., D. J. Southwood, E. J. Smith, and A. Balogh, A survey of low frequency waves at Jupiter: The ULYSSES encounter, *J. Geophys. Res.*, *98*, 21,203, 1993b.

Wilson, L. B., III, C. A. Cattell, P. J. Kellogg, K. Goetz, K. Kersten, J. C. Kasper, A. Szabo, and K. Meziane, Low-frequency whistler waves and shocklets observed at quasi-perpendicular interplanetary shocks, *J. Geophys. Res.*, *114*(A13), A10106, 2009.

Zhang, T. L., J. G. Luhmann, and C. T. Russell, The magnetic barrier at Venus, *J. Geophys. Res.,* , *96*, 11,145–+, 1991.

Zhang, T. L., et al., Magnetic field investigation of the Venus plasma environment: Expected new results from Venus Express, *Planet. Space. Sci.*, *54*, 1336–1343, 2006.

Zhang, T. L., et al., Induced magnetosphere and its outer boundary at Venus, *Journal of Geophysical Research (Planets)*, *113*(E12), E00B20, 2008.

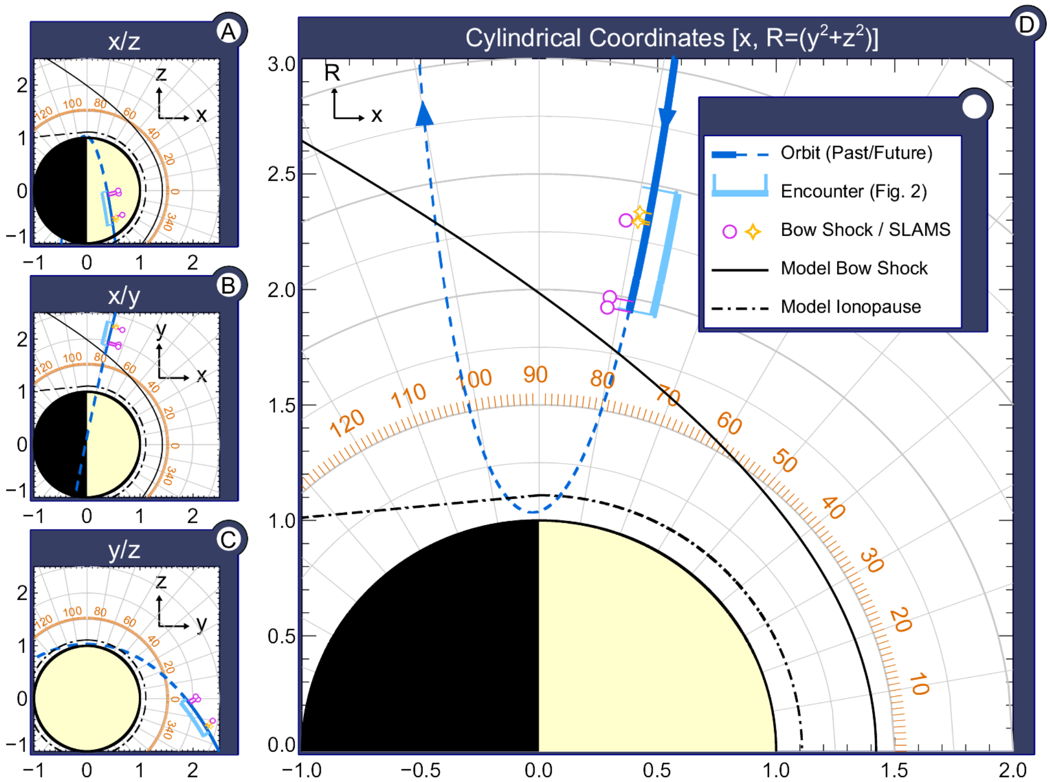

Figure 1. Map of the encounter on the 11th of April 2009, showing the trajectory of *Venus Express* (dark blue line), idealized bow shock according to *Slavin et al.* [1980] (black line), actual bow shock crossings, and the distance covered by the spacecraft during the period covered by Figure 2. Panels A-C are in VSO co-ordinates, Panel D in Cylindrical co-ordinates, where the x-axis points towards the sun, and the y-axis is the radial distance ($R = \sqrt{y^2 + z^2}$) from the Venus/Sun line. All units are in Venus Radii.

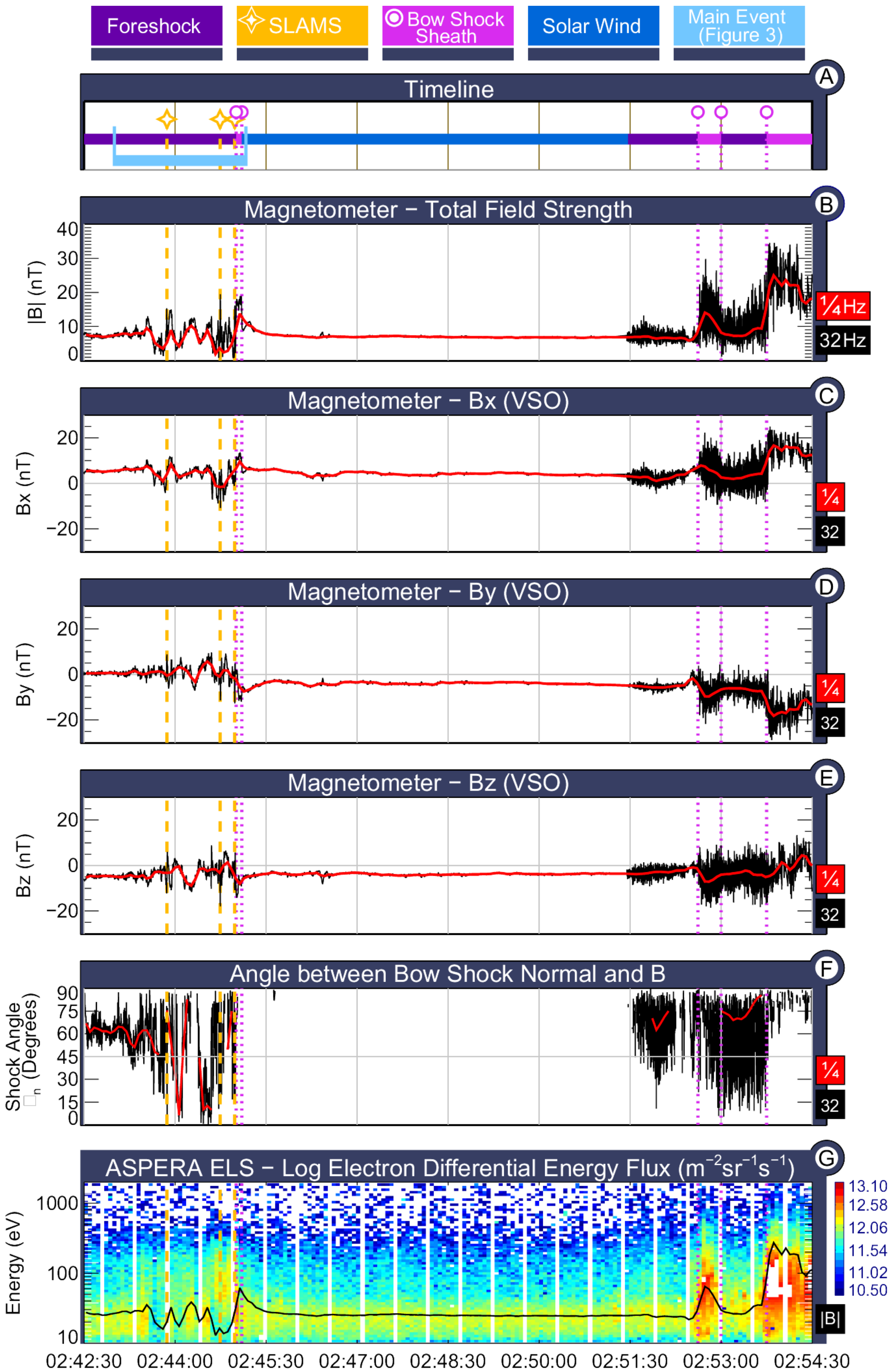

Figure 2. Data from the *Venus Express* on the 11th of April 2009 covering a period from 2:42:30 to 2:54:30 Greenwich Mean Time.

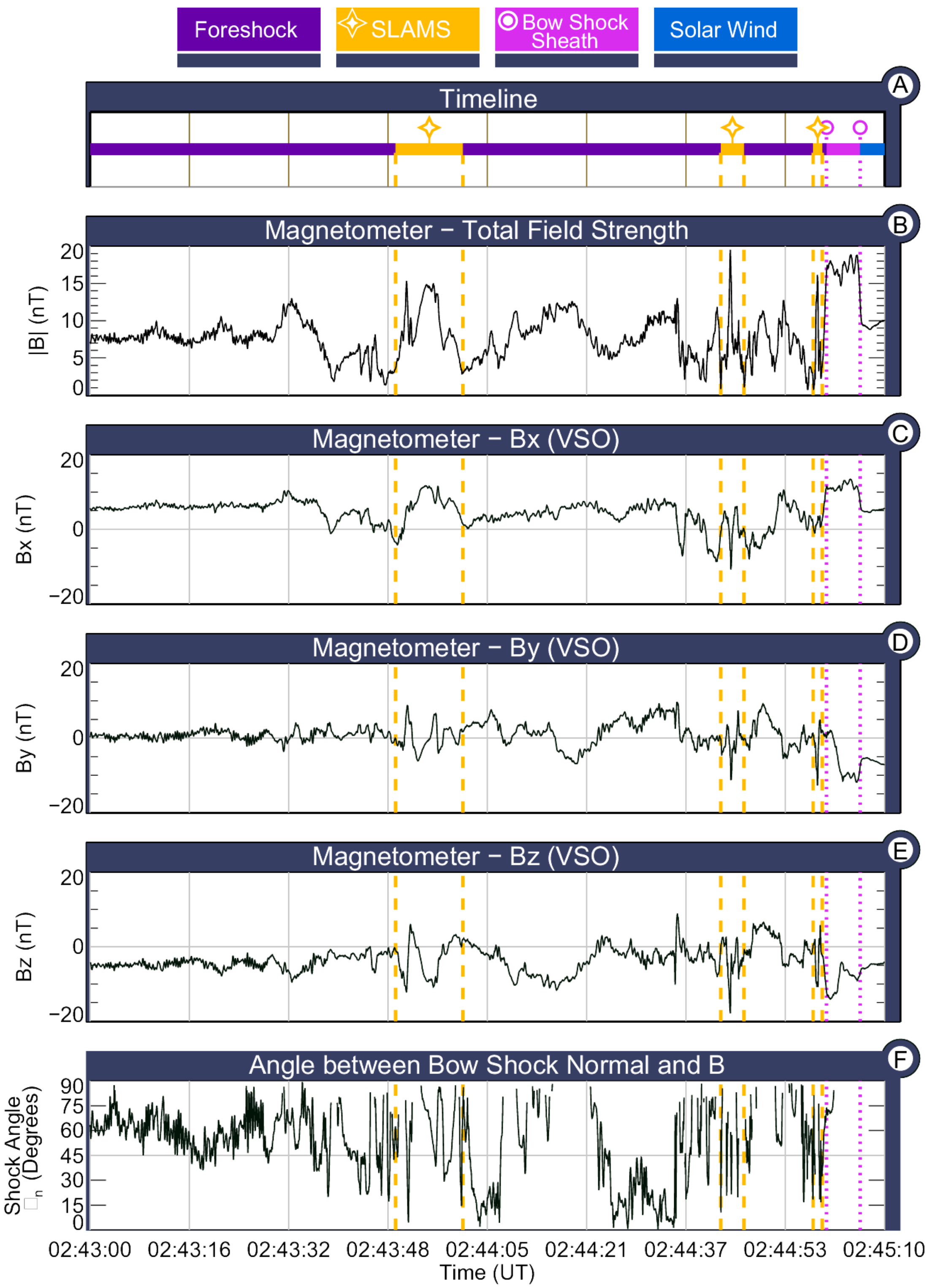

Figure 3. Data from the *Venus Express* on the 11th of April 2009 covering a period from 2:43:00 to 2:45:10 GMT.

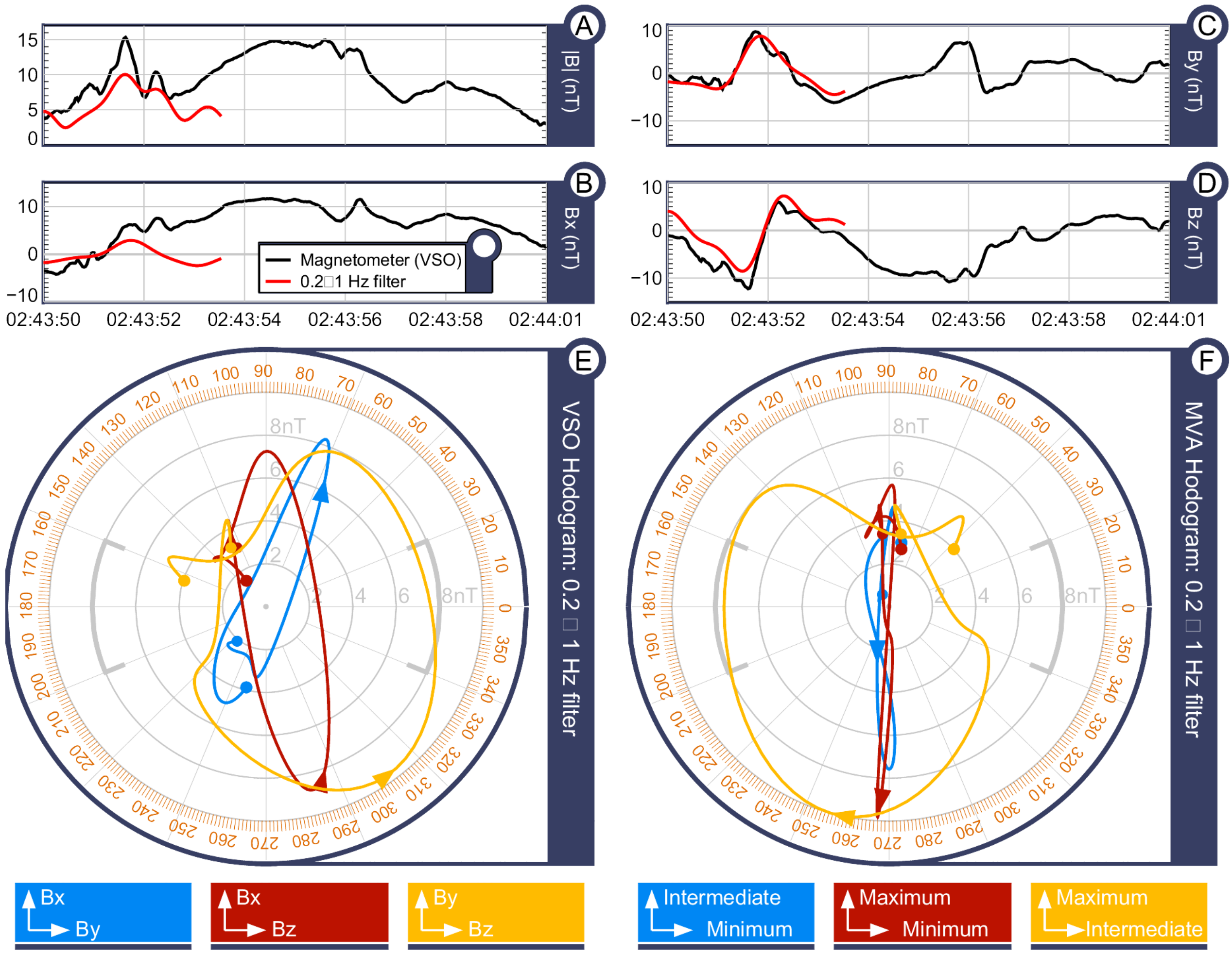

Figure 4. Panels A-D: The magnetic signature of the elliptically polarized field spike within an example of Cytherean SLAMS, at ~02:43:51 GMT. Panel E: Hodograms of the same data after it has been processed with a $0.2 \rightarrow 1Hz$ filter. Panel F: Hodogram of the same data in minimum variance coordinates showing the elliptical polarization of the SLAMS and full 360° rotation.