

Foreshock cavities at Venus and Mars

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Key Points:

- We report the existence of foreshock cavities at Venus and Mars
- They are common and have properties similar to those at Earth
- They are the result of transient encounters with a planetary foreshock

Abstract

“Foreshock cavities” are regions of turbulent and heated solar wind plasma that form upstream of Earth’s bow shock. Despite being common at Earth, none have yet been reported at other planets. Here we present a survey of events encountered by the ESA *Venus Express* spacecraft consistent with foreshock cavities at Venus, and a case study of a foreshock cavity encountered at Mars by NASA’s *MAVEN* orbiter. Cavities appear to be common at Venus, and that their properties appear to be very similar to those at Earth. Foreshock cavities appear to be observed preferentially in fast solar wind, and when the interplanetary magnetic field is “radial” (parallel to the Sun-Planet line). Our collected observations are consistent with the hypothesis that “foreshock cavities” are simply the result of a transient encounter with a planetary foreshock. We posit foreshock cavities represent one of the following two possibilities: **(1.)** A spacecraft encountering a traveling foreshock formed by a finite bundle of interplanetary magnetic field lines connecting to a shock, or **(2.)** the transient temporary motion of the foreshock over the spacecraft.

1 Introduction to foreshock cavities

The foreshock is the region of space upstream from and in magnetic connection to a planet’s bow shock (Eastwood et al., 2005), first discovered at Earth by the American *Vela* fleet of nuclear test-ban monitoring satellites (Asbridge, Bame, & Strong, 1968; Greenstadt et al., 1968). Within the foreshock, counter-streaming particles reflected from the shock form unstable plasma distributions (e.g. Frank, Paterson, Ackerson, Coroniti, & Vasyliunas, 1991; Moore, McComas, Russell, & Mihalov, 1989; Yamauchi et al., 2011) which are a source of free energy for waves (G. A. Collinson, Sibeck, et al., 2012; Gurnett et al., 1991; Hoppe & Russell, 1981). At the Earth, these particles and waves generate and drive a cornucopia of transient, and sometimes explosive, plasma phenomena. Foreshock processes play an important role at Earth, having a global impact on our magnetosphere (Eastwood et al., 2008; Jacobsen et al., 2009) and ionosphere (Sibeck et al., 1999; Sibeck, Borodkova, Zastenker, Romanov, & Sauvaud, 1998). They also play a central role in the fundamental process of acceleration of particles at the bow shock (Turner et al., 2018).

Foreshock cavities are regions of heated solar wind plasma, with depressed densities and magnetic strengths and enhanced wave activity (Sibeck, Phan, Lin, Lepping,

51 & Szabo, 2002), bounded by regions of enhanced magnetic field strength and density, called
 52 the “*foreshock compressional boundary*” (FCB) (Omidi, Sibeck, et al., 2013; Omidi, Sibeck,
 53 & Blanco-Cano, 2009; Sibeck, Omidi, Dandouras, & Lucek, 2008). Foreshock cavities are
 54 very large with respect to the size of the system ($\sim 30R_E$ across at Earth, (Y. Lin, 2003;
 55 Omidi, 2007; Turc et al., 2018)), and encounters with cavities at Earth often last for 5-
 56 10 min or longer. Cavities are very common: many tens of cavities can occur each day
 57 at Earth (e.g. Sibeck et al., 2001). Foreshock cavities have been shown to drive large-
 58 scale disruptions in Earth’s magnetosphere: When foreshock cavities lie directly upstream
 59 from the Earth’s sub-solar magnetopause, the pressure applied to the magnetosphere di-
 60 minishes (Fairfield, Baumjohann, Paschmann, H., & Sibeck, 1990) and large-amplitude
 61 transient events are common in both the outer magnetosphere (Hartinger, Turner, Plaschke,
 62 Angelopoulos, & Singer, 2013) and at the footprints of these magnetic field lines in the
 63 high-latitude ionosphere (Sibeck et al., 2003), suggesting that the cavities and their bound-
 64 aries drive large-amplitude bow shock (Korotova, Sibeck, Omidi, & Angelopoulos, 2012)
 65 and magnetopause motion (Korotova, Sibeck, Rosenberg, Russell, & Friis-Christensen,
 66 1997). Foreshock cavities also impact Earth’s ionosphere: Murr and Hughes (2003) showed
 67 that foreshock cavities trigger cyclonic magnetic field and electrical current in Earth’s iono-
 68 sphere, 1000-3000km across, known as traveling convection vortices (Friis-Christensen,
 69 McHenry, Clauer, & Vennerstrøm, 1988).

70 To date, foreshock cavities have only been identified upstream of Earth (Sibeck et
 71 al., 2002), where the obstacle to the solar wind is Earth’s internally generated dipole mag-
 72 netic field. It is not necessarily a foregone conclusion that foreshock cavities can occur
 73 at every astrophysical shock, especially planets without a magnetic field such as Venus
 74 and Mars (Smith, Davis, Coleman, & Jones, 1965b; Smith, Davis, Coleman, & Sonett,
 75 1965a), where the obstacle to the solar wind (the “*induced*” magnetosphere) is an order
 76 of magnitude smaller (Ness, Behannon, Lepping, Whang, & Schatten, 1974; Russell, El-
 77 phic, & Slavin, 1979; Slavin et al., 1980a) than at Earth.

78 In this study, we address four scientific questions:

79 **Q1.** Are foreshock cavities observed at unmagnetized planets?

80 **Q2.** What are the properties of foreshock cavities at Venus?

81 **Q3.** What causes foreshock cavities?

82 **Q4.** What is the impact of foreshock cavities on Venus?

Our primary focus is on the planet Venus, being the closest planetary analog to Earth in terms on size and ionospheric density, and getting the best possible picture of what Earth’s solar wind interaction might be like if our planet did not generate a magnetic dipole field. We will primarily use data from the European Space Agency (ESA) *Venus Express* (VEx) spacecraft (2006-2014) (Svedhem et al., 2007). Additionally we briefly present a case study of a likely foreshock cavity at Mars as encountered by the National Aeronautics and Space Administration (NASA) Mars Atmosphere and Volatile Evolution (*MAVEN*) spacecraft (2014 - present) (Jakosky et al., 2015), to establish their existence at Mars, strongly suggesting foreshock cavities to be a universal phenomena.

This paper is laid out as follows. In section 2 we present case studies of foreshock cavities at Earth, Venus, and Mars. In section 3 we present the results of the first extraterrestrial survey of foreshock cavities at the planet Venus. In section 4 we combine our collected observations at Mars and Venus with the Omidi, Collinson, and Sibeck (2020) 3D hybrid models of foreshock cavities at Venus to discuss the apparent formation mechanism for foreshock cavities. In section 5 we examine a multi-hour encounter by *Venus Express* with a static and quasi-stable foreshock cavity to examine their impact on the induced magnetosphere and ionosphere, and compare our findings to recent observations at Mars. Finally, in section 6 we summarize our findings and the extent to which we can answer the four scientific questions above.

2 Case Studies of foreshock cavities at Earth, Venus, and Mars

There is a substantial body of evidence which suggests that foreshock cavities should form at all bow shocks, even those of unmagnetized planets. Recent hybrid simulations of the Venusian foreshock by Omidi, Collinson, and Sibeck (2017) predicted the formation of a stable foreshock cavity that formed when the interplanetary magnetic field (IMF) is “radial”, or parallel to the Sun-Venus line. Additionally, collected observations by *Venus Express* and *MAVEN* strongly suggest that the foreshocks of unmagnetized planets are just like at Earth, albeit in miniature. So far, the foreshocks of Venus and Mars have been shown to contain the same phenomena as Earth, albeit scaled down in proportion to the size of the solar wind obstacle (G. Collinson et al., 2015, 2017; G. A. Collinson, Sibeck, et al., 2012; G. A. Collinson et al., 2014; G. A. Collinson, Wilson, et al., 2012; Slavin et al., 2009; Yamauchi et al., 2011). Thus, the universal existence of foreshock cavities at Venus and Mars seems highly likely.

In this paper, we examine case studies from three planets (Earth, Venus, Mars), to establish that foreshock cavities are likely a universal phenomenon, found upstream of every astrophysical bow shock. In Section 2.1 we first briefly review an example of an established foreshock cavity upstream of Earth (Sibeck et al., 2002). Then in Section 2.2 present two case-study examples of foreshock cavities at Venus, as observed by the ESA *Venus Express*, establishing their existence at other planets. Then, in Section 2.3, we briefly turn our attention to Mars, presenting a case-study of a Martian foreshock cavity as encountered by *MAVEN*, suggesting that they are a universal phenomenon observed upstream of every astrophysical bow shock.

2.1 Review of example foreshock cavity at Earth

Before we venture to other planets, we shall review the distinguishing characteristics of foreshock cavities by briefly re-examining an established example that was encountered upstream of Earth’s bow shock. Figure 1 shows the Sibeck et al. (2002) foreshock cavity, which was encountered by NASA’s *Wind* spacecraft on the 19th of April 1999, far upstream of Earth’s equatorial dawn bow shock. Figure 1D shows a map of the encounter, in cylindrical geocentric solar magnetospheric co-ordinates (GSM), where the x-axis points from the center of Earth towards the sun, and the R-axis is the radial distance from the Sun-Earth line.

Wind measured a crater-like depression in magnetic field strength (the cavity), bounded by brief enhancements in field strength (the foreshock compressional boundaries) (Fig. 1B). Inside the foreshock cavity, the magnetic field was highly turbulent. Measurements by the *Wind* Ion Spectrometer (PESA) (R. P. Lin et al., 1995) (Fig. 1C) reveal that plasma densities are highly correlated with magnetic field strength. The temperature of superthermal ions (measured by PESA-H) was elevated in the cavity, whereas the temperature of core of the solar wind population (measured by PESA-L) was slightly depressed.

At first glance, a foreshock cavity shares many common characteristics with the “zoo” of other phenomena found in the foreshock, such as Hot Flow Anomalies (Schwartz, 1995; Thomsen et al., 1993) (HFAs), Spontaneous HFAs (Omidi, Zhang, Sibeck, & Turner, 2013; Zhang et al., 2013), and Bubbles (Turner, Omidi, Sibeck, & Angelopoulos, 2013). However, several features distinguish foreshock cavities from these other transients. First and foremost, they can be physically far larger than any other foreshock phenomena, com-

parable to the size of the magnetosphere itself (Y. Lin, 2003; Omidi, 2007; Turc et al., 2018). Thus, an encounter with Earth’s foreshock cavities can last for several minutes, whereas other foreshock transients tend to last for only tens of seconds. By way of example, the Sibeck et al. (2002) event (Fig. 1) exhibits just such a long duration, lasting for nearly 5 minutes.

A second differentiating property of cavities is that, while some other foreshock transients (HFAs, Bubbles) always form around a “discontinuity” in the IMF (e.g. an abrupt change in the average direction), this does not appear to be an absolute requirement for the observation of a foreshock cavity. For example, that there is no significant change in the direction of the IMF before or after the Sibeck et al. (2002) event (Fig. 1), and thus there is no clear evidence that this cavity is centered on an IMF discontinuity. However, other cavities have been reported to be associated with an IMF discontinuity (e.g. Billingham, Schwartz, & Wilber, 2011).

This said, during the event, the Bx and By components of the magnetic field diminish, suggesting that the cavity may be associated with a brief rotation in the interplanetary magnetic field. If so, then a simple explanation for this event would be that this brief rotation briefly brought *Wind* into and out of Earth’s foreshock, where plasma temperatures are higher, densities are lower, and the magnetic field is more turbulent and full of waves.

2.2 A foreshock cavity at Venus

Omidi et al. (2017) recently employed a 3D hybrid model to predict the presence of a foreshock cavity upstream of Venus. To test this prediction and investigate whether they exist at Venus, we visually surveyed the entire *Venus Express* dataset, examining periods when the spacecraft was upstream of the Bow Shock. This search yielded 15 firm candidates, whose properties are entirely consistent with foreshock cavities encountered at Earth (e.g. Billingham et al., 2011; Murr & Hughes, 2003; Sibeck et al., 2002), and with our simulations. In this Section (and Figures 4 and 3) we present our two best examples (event №10 and event №15), and later in Section 3, we describe the general properties all 15 Venusian foreshock cavities so far discovered.

Location: Figure 4 shows a map of two orbits of the ESA *Venus Express* in the Venus-centric “*Venus Solar Orbital*” (VSO) coordinates, where the x-axis points towards

the sun, the y-axis points back along the tangent of the orbital plane of Venus, and the z-axis completes the right-handed set, pointing up out of the ecliptic. Figure 4D shows the locations of events №10 and №15 with respect to the Slavin et al. (1980a) Venus model bow shock. Both events were encountered in the Venusian foreshock, exactly where one would expect to see a foreshock cavity.

Venus Express Instrumentation: Figure 3 shows *Venus Express* observations of magnetic fields and superthermal electrons from two likely foreshock cavities at Venus. In this study we use data from the *Venus Express* Magnetometer (MAG) (Zhang et al., 2006) (at 1Hz survey resolution) and the Analyzer for Space Plasmas and Energetic Atoms Electron Spectrometer (ASPERA-4 ELS) (Barabash et al., 2007; G. A. Collinson et al., 2009). Caution must be used when interpreting *Venus Express* ELS data, since the sensor had a limited (2D) field of view. The electron moments presented in this study were calculated assuming isotropy, and therefore should be considered pseudomoments. While *Venus Express* carried a 3D Ion Mass Spectrometer (IMA), its temporal resolution was too slow (192s) to calculate meaningful plasma moments for these events.

Event №10 (Fig. 3A-C) was previously reported by G. A. Collinson et al. (2014), and initially identified as an unusually long-duration (2 minute) Venusian hot flow anomaly. However, following our recent series of hybrid simulations (Omidi et al., 2017), and a complete survey of all *Venus Express* foreshock data, we now reclassify this event as an encounter with a Venusian foreshock cavity. Event №10 is almost identical in overall character to the Sibeck et al. (2002) foreshock cavity at Earth. Event №15 (Fig. 3D-F) is of even longer duration (4 minutes) and exhibits milder conditions inside the cavity.

IMF conditions: During both events, the magnetic field was in contact with the bow shock at an angle $\theta_n = 45^\circ$. Like the Sibeck et al. (2002) event, there is no apparent change in the orientation of the interplanetary magnetic field (IMF) before and after the event, suggesting that this event was not centered by an IMF discontinuity. However, inside the cavity, the IMF is at a distinctly different orientation than in the surrounding foreshock. Outside of event №15, the IMF had a B_z component of approximately $8nT$, whereas inside the cavity, the mean value of this component reduced to close to $0nT$, leaving the magnetic field to be dominated by B_x and B_y . A change in magnetic field components was also observed inside event №10, although the overall magnitude of the magnetic field diminished due to a diamagnetic effect associated with the hot plasma within

the cavity. In each cavity, the magnetic field was highly turbulent and full of waves, consistent with encounters with terrestrial foreshock cavities.

Foreshock compressional boundaries: As with the Sibeck et al. (2002) foreshock cavity at Earth, both events were flanked by gentle enhancements in both magnetic field magnitude ($|B|$), consistent with a crossing of the foreshock compressional boundary. In both cases plasma densities were elevated inside the Foreshock Compressional Boundaries (FCBs), but there was no evidence for an increase in plasma temperature. However, as noted previously, caution must be taken when interpreting ASPERA-ELS pseudomoments (especially temperature, which is a higher order moment than density), due to the limited, 2D, field of view of the instrument.

Conditions inside the foreshock cavity: Consistent with the Sibeck et al. (2002) event at Earth, inside the cavity of event №10, the magnetic field magnitude ($|B|$) was weaker and more turbulent. Electron densities were consistent with or slightly lower than in the solar wind, and temperatures were substantially elevated in event №10 (Fig. 3C). Similar (although less prominent) conditions were observed during the first $\approx 25s$ of the cavity of event №15. After this, Event №15 was filled with oscillating periodic magnetic waves, exactly as predicted by hybrid simulations of a Venusian foreshock cavity by Omidi et al. (2017). Electron densities and temperatures inside event №15 appeared less perturbed (Fig. 3H). The Ultra-Low Frequency waves (ULF) encountered within event №15 are consistent with the proton cyclotron waves commonly observed upstream of Venus, on magnetic field lines connected to the bow shock (Delva et al., 2008; Shan et al., 2016).

Duration and size estimates: As with the Sibeck et al. (2002) cavity at Earth, both events lasted for several minutes (Event №10, ≈ 2.25 mins, Event №15, ≈ 3.5 mins). If we assume they are simply convecting along with the solar wind, then №10 would be 7.7 Venus Radii (R_V) across, and №15 would be $11.1R_V$ across, due to the solar wind speeds of $376km/s$ and $399km/s$ respectively.

If it were standing rigidly in place as a perfectly static structure, №10 would be only $0.16R_V$ across, and №15 $0.25R_V$ (from the distance that *Venus Express* moved). Previous hybrid simulations of a Venusian foreshock cavity by Omidi et al. (2017) predict that they should be approximately $2R_V$ across, an order of magnitude larger than the $0.16R_V$ from the purely static assumption.

Thus, these results suggest that this event was neither convecting along with the solar wind, nor stationary with respect to the planet. This suggests a traveling structure, attempting to move upstream against the flow of the solar wind, but being blown back towards the bow shock. If we assume the actual dimensions of the foreshock cavity to be $2R_V$, then №10 and №15 would be moving downstream (with respect to Venus) at a velocity of 85 km/s and 53 km/s , respectively, or $\approx 23\%$ and $\approx 13\%$ of the velocity of the ambient solar wind.

With only a single spacecraft, it is challenging to get an accurate quantitative picture of the physical size of these events, but qualitatively, these observations suggest a very large structure, comparable in size to the entire induced magnetosphere of Venus.

2.3 A foreshock cavity at Mars

On the 4th of January 2016 NASA’s *MAVEN* Mars Orbiter encountered a similar event consistent with an encounter with a foreshock cavity. Figure 4 shows a map of the encounter in “Mars Solar Orbital” (MSO, equivalent to VSO), showing the orbit of *MAVEN*, model bow shock and magnetopause according to (Vignes et al., 2000), and the location of the encounter with the foreshock cavity. Figure 5 shows *MAVEN* data from this encounter, with 5A showing a color coded timeline of the event, with the foreshock in blue, the cavity in gold, and the foreshock compressional boundaries in purple (as before).

Location: As with the Venusian case studies (Figure 4), the event was encountered upstream of the Martian Bow Shock, in the foreshock, the region of space where one would expect to encounter a foreshock cavity.

***MAVEN* Instrumentation:** Figure 5B shows magnetic observations by the *MAVEN* Magnetometer (MAG) (Connerney et al., 2015); magnetic magnitude ($|B|$); three vector components in MSO; each vector is projected to the location of an idealized model bow shock (Vignes et al., 2000) and the angle which it makes to the bow shock normal vector $\theta_{\hat{B} \cdot \hat{n}}$ is shown in the bottom panel. Figure 5C shows ion observations from the Solar Wind Ion Analyzer (SWIA) (Halekas et al., 2015); a time/energy ion spectrogram; ion density cm^{-3} , ion temperature (eV), and three component velocity (km/s) at 4s cadence. Figure 5D shows superthermal electron observations by the *MAVEN* Solar Wind

Electron Analyzer (SWEA) (Mitchell et al., 2016); a time/energy spectrogram, electron density cm^{-3} , and electron temperature (eV) at 1s cadence.

Location and IMF conditions: At 13:35:30 Greenwich Mean Time (GMT), *MAVEN* was upstream of the bow shock of Mars, with local interplanetary magnetic field lines making contact with the bow shock ($\theta_{\hat{B}, \hat{n}} \approx 45^\circ$), the correct location where one would expect to encounter the foreshock cavity. As with the two candidate events at Venus (Fig. 3), and the Sibeck et al. (2002) foreshock cavity, there was no appreciable change in the orientation of the interplanetary magnetic field (IMF) before and after the event.

Foreshock compressional boundaries: As with the events at Earth and Venus, this Martian foreshock cavity candidate was bounded by regions of slightly enhanced magnetic field magnitude ($|B|$) and plasma density, consistent with an encounter with the foreshock compressional boundary (purple, Fig. 5A). Neither ion nor electron temperature were significantly enhanced in the Foreshock Compressional Boundaries, consistent with the events at both Earth and Venus.

Conditions inside the foreshock cavity: The core of the event (gold, Fig. 5A) exhibited weak turbulent magnetic fields (Fig. 5B); lower plasma densities (Fig. 5C,D); and elevated ion temperatures (Fig. 5C) and electron temperatures (Fig. 5D); all consistent with an encounter with a foreshock cavity. Inside the cavity, the B_z component of the magnetic field drops to close to $0nT$, from the $3nT$ in the surrounding foreshock and boundaries. The magnetic field was highly turbulent, with $\theta_{\hat{B}, \hat{n}}$ oscillating wildly.

Duration: Finally, consistent with an encounter with the foreshock cavity at Venus, this event lasted for several minutes (≈ 3.5). This is far longer than encounters with other types of common foreshock transients at Mars such as “classical” hot flow anomalies (60 seconds (G. Collinson et al., 2015; Øieroset, Mitchell, Phan, Lin, & Acuña, 2001)) and “spontaneous” hot flow anomalies (12 seconds (G. Collinson et al., 2017)). As with our Venusian example, this suggests a very large structure, comparable in size to the Martian induced magnetosphere.

3 A survey of foreshock cavities at Venus

In this section we examine the typical properties of foreshock cavities at Venus (unmagnetized) and compare them to those at Earth (magnetized). We visually surveyed the entire *Venus Express* data set, looking for events similar to the case studies shown

in Figure 3. Specifically, we looked for isolated intervals of turbulent IMF, with compressional boundaries, several minutes in duration. Since this is a subjective approach, we cannot expect to capture every single cavity encountered by *Venus Express*. However, this approach will enable a first-order statistical examination of the collective properties of the 15 very best and most unambiguous foreshock cavity candidates.

Figure 6 shows 10 minute long data plots of *Venus Express* magnetic fields and electron energy spectrograms from all 15 events. Each plot includes a color-coded timeline, showing foreshock (blue), foreshock compressional boundaries (purple), and the cavity itself (gold). Table 1 accompanies Figure 6, shows the attendant conditions in the interplanetary magnetic field and solar wind, and compares them to typical properties of cavities at Earth ($\oplus$) and IMF/solar wind at Venus ($\odot$).

The durations of the events varied widely between 59s (N^o7) and 497s (N^o6), consistent with cavities at Earth (Billingham, Schwartz, & Sibeck, 2008), although the number of events is too few for a meaningful statistical comparison of duration. The mean strength of the interplanetary magnetic field ($|B| = 6.2 \pm 2.5 nT$) and mean density of the solar wind ($5.4 \pm 3 cm^{-3}$) in which the foreshock cavities were embedded were within the normal range (Collinson et al., 2015). On average there was an 18° change in the orientation of the IMF angle (in both θ and ϕ) before and after *Venus Express* encountered a cavity. However, a change in IMF orientation does not appear to be an absolute requirement to observe a cavity, since for one third of the events (N^os 1,7,10,11,15), the IMF remained constant in both orientation and strength before and after passing through the cavity.

All events were encountered within approximately 15 minutes of crossing the bow shock. For a very rough first-order estimation of the occurrence rate of foreshock cavities at Venus, let us assume that out of the approximately 3,000 orbits of *Venus Express*, each orbit taking ~ 24 hours, that there were only 45,000 minutes (~ 31 Earth days) where it would have been possible to encounter a cavity. This suggests that a lower bounds on the occurrence rate of cavities at Venus is ≈ 1 every 48 hours. Given the poor statistics and relative paucity of data from this narrow region of space upstream of the Venusian bow shock, it is entirely possible that the actual rate is far higher, and closer to the terrestrial rate of tens per day (Sibeck et al., 2001). However, what can be stated with certainty is that foreshock cavities appear to be common at Venus.

One stand-out property of the Venusian foreshock cavities is that they were all observed during faster than typical solar wind velocities. The mean solar wind velocity for the 15 events was $459 \pm 82 \text{ km/s}$, whereas the mean solar wind velocity measured by the *Venus Express* ASPERA Ion Mass Analyzer was closer to 360 km/s (Collinson et al., 2015). This is consistent with studies of foreshock cavities at Earth by Sibeck et al. (2001) and Billingham et al. (2008), who also found that cavities preferentially occur during high speed solar wind.

Another stand-out property is that cavities tended to be observed when the IMF was near to “radial”, or in other words, oriented close to the Sun-Venus line. At Venus, the IMF has a mean Parker spiral angle of 36° (Slavin & Holzer, 1981), and the mode IMF cone angle during the *Venus Express* mission was 42° (Collinson et al., 2015). However, the mean angle of the IMF for the 15 cavity candidates was 7.2° (Table 1).

In the foreshock compressional boundaries, the mean magnetic field strength was on average 1.3 times higher than in the surrounding foreshock. On average the field inside the cavity was 1.4 ± 0.5 higher than that in the foreshock, consistent with observations of cavities at Earth by Sibeck, Baumjohann, and Lopez (1989). However, the field inside the cavities (by selection) was highly turbulent and full of waves, and thus a “mean” magnetic field strength is less meaningful here since it is so variable.

Figure 7 shows a map of the location of the 15 foreshock cavities in cylindrical VSO-coordinates (x , R), where x points towards the sun, and the R -axis denotes the distance from the Sun-Venus line. By taking the mean IMF orientation from these locations (both before and after the cavities), one may extrapolate to where the IMF touches a nominal hyperbolic bow shock (according to Slavin et al. (1980b)), and calculate the angle the IMF makes to the bow shock normal ($\Theta_{\hat{B}, \hat{n}}$, table 1). In all cases, we predict that the IMF was in contact with the bow shock, and thus the *Venus Express* was in the foreshock during the events.

If these cavities were convecting with the solar wind, then the mean size of the 15 cavities would be $15 \pm 10 R_V$. As with our previous case studies, while it is difficult with only a single spacecraft to accurately determine the size of these structures, these results strongly suggest that, if they do convect with the solar wind, then they are of a size that is comparable to the entire induced magnetosphere.

4 The formation of foreshock cavities

Two distinctly different models of foreshock cavity formation have been proposed. According to Billingham et al. (2011) the cavities lie on regions of IMF lines connected to the bow shock sandwiched between compressional boundaries located on regions of magnetic field lines that do not connect to the bow shock. If so, the events are bounded by rotational or tangential discontinuities rather than centered on them as in the case of HFAs. Furthermore, they would convect antisunward with the discontinuities and solar wind flow. In the alternative scenario, the boundaries form in the absence of any IMF discontinuities within regions of magnetic field lines connected to the bow shock (Omidi et al., 2009; Omidi, Zhang, et al., 2013). If so, foreshock cavities can stand in place, and need not convect anti-sunward with the solar wind flow.

Observations at both Venus and Mars strongly suggest that foreshock cavities form within regions of magnetic field lines connected to the bow shock, without the need for an IMF discontinuity. To illustrate this mechanism, Figure 8 shows the results from a 3D hybrid model showing the formation of foreshock cavities (full details of the simulation can be found in a companion paper, (Omidi et al., 2017)). Figure 8A shows a schematic of the upstream Venusian region and its foreshock cavities (FC). Figure 8B shows simulated magnetic field magnitude (with respect to the background IMF strength), 8C and 8D show plasma density and temperature with respect to the solar wind. In all cases, the sun is off to the left with the solar wind flowing from left to right.

The Venusian induced magnetosphere was simulated under two different orientations of the interplanetary magnetic field. The simulation was initialized under “radial” conditions, with the IMF parallel to the Sun-Venus line (simulation time $t = 0$, left hand panels), similar to the conditions at Venus (and Mars) where foreshock cavities were observed. A foreshock cavity formed instantly in the simulation, wherever the IMF touched the bow shock. Solar wind protons were reflected from the simulated bow shock, generating a region upstream of the bow shock permeated by ULF waves (the cavity) (Omidi et al., 2017), and bounded by regions of enhanced density and magnetic field strength (the foreshock compressional boundaries).

Halfway through the simulation, a simulated discontinuity in the IMF was introduced into the model, with the IMF rotating to a more typical parker spiral angle of 36° . After the simulated IMF discontinuity had passed (simulation time $t = 557$, right pan-

els) the Venusian induced magnetosphere regained a new equilibrium state under a Parker spiral angle of 36° , and still exhibited an upstream foreshock cavity wherever the IMF made contact with the bow shock. However, whereas at 0° IMF the interior of the cavity was a regular series of ULF waves which would be easily observable in spacecraft data, at 36° , the structure within the cavity was smoother and more complex.

These simulations are entirely consistent with observations, whereby the magnetic field remained in contact with the bow shock throughout the encounter with the cavity at both Venus (Fig. 3 B,E: θ_n) and Mars (Fig. 5 B, θ_n). While some events were associated with a change in IMF orientation, this was not always the case. As shown in the simulation, a change in the orientation of the IMF will result in a shift in the location of the foreshock. Thus, one likely explanation for the occasional observation of cavities in association with an IMF discontinuity is that the a foreshock cavity is simply a transient encounter with the foreshock.

Based on our collected observations and the results of the hybrid simulations, we posit that foreshock cavities can represent one of the following two possibilities: **(1.)** A spacecraft encountering a traveling foreshock formed by a finite bundle of interplanetary magnetic field lines connecting to a shock (ala Billingham et al. (2011)), as in our case studies at Venus (events №10 and №15, Fig. 3) and Mars (Fig. 5), whereby there was a brief rotation in the IMF associated with entry and exit into the core of the foreshock cavity. **(2.)** A brief transient motion/passage of the foreshock over the spacecraft (i.e. crossing the FCB into the foreshock and back through the FCB into the solar wind, ala Omidi et al. (2009)), resulting from the re-orientation of the foreshock by a discontinuity in the IMF (e.g. Venus events №2, №9, №11, №12 in Fig. 6; or our hybrid simulations in Fig. 8). Thus, both proposed formation models are valid, and either may result in the observation of a foreshock cavity.

“Radial” IMF (i.e. closely aligned with the Sun-Planet line) appears to be particularly conducive to the observation of a cavity. We posit that this is because the more radial the IMF, the longer time any particular magnetic field line has to be in contact with the bow shock, and the stronger and more extended the foreshock interaction will be. Conversely, when the IMF is oriented at 90° tangential to the Sun-Planet line, it is rapidly blown over the bow-shock by the solar wind and there is less time for it to interact and form a strong foreshock. We therefore hypothesize that cavities may be less

common at planets orbiting far from their star, where the parker spiral angle is close to 90° .

5 The impact of the foreshock cavities at unmagnetized planets

In section 4, we posited that foreshock cavities appear to be the result of transient passages into the foreshock under “radial” IMF conditions. Over the course of the ~ 8 Earth years that the *Venus Express* was in orbit, there were occasions when the IMF remained in a stable “radial” orientation for many hours, creating upstream conditions directly comparable to those in our hybrid simulations (Fig. 8). Such steady-state upstream conditions permit us, with a single spacecraft, to probe the extent and structure of the foreshock cavity, and its impact on the induced magnetosphere and ionosphere.

5.1 A stable foreshock cavity at Venus - 13th September 2010

Figure 9 shows perhaps the best example of stable “radial” IMF conditions (and the resulting foreshock cavity) during the *Venus Express* mission. Figure 9A shows a map of the orbit of the *Venus Express* on the 13th of September 2010, in cylindrical VSO coordinates. At 06:00 Greenwich Mean Time (GMT), the *Venus Express* was at an altitude of $5R_V$, was approximately $2R_V$ upstream of the planet, and would not cross the bow shock for over two hours. At approximately 06:05 GMT, *Venus Express* began to encounter Ultra-Low Frequency waves (Fig. 9C) consistent with proton cyclotron ULF commonly observed in the foreshock of Venus (Delva et al., 2008; Shan et al., 2016), and consistent with those in our simulated foreshock cavity (Omidi et al., 2020). These waves were observed continuously until the *Venus Express* crossed the bow shock at approximately 08:23 GMT.

These observations are consistent with the *Venus Express* flying through a quasi-static and stable foreshock cavity, similar in size to the entire induced magnetosphere, just as predicted by our hybrid simulations (fig. 8, (Omidi et al., 2017, 2020)). The internal conditions, and physical size ($\geq 5R_V$), are consistent with the transient foreshock cavities presented previously in this paper ($14.7 \pm 10R_V$). This further supports the hypothesis that “foreshock cavities” are simply the transient passage of the foreshock over a spacecraft. Unlike the transient cavities, passage through the foreshock compressional boundary is less clear in this static example. *Venus Express* observed a gradual increase

in magnetic field magnitude over the course of 5 minutes (color coded purple in Fig. 9, $\sim$ 06:04 to 06:08 GMT), consistent with what might be expected from passage into highly dynamic foreshock boundaries.

While only a single case study, the data from this orbit where the IMF was both radial and stable make it ideal to search for evidence of any effect of the foreshock cavity on the induced magnetosphere and ionosphere of Venus. Figure 9D-F show a close-up of 20 minutes data covering the passage of the *Venus Express* from the foreshock (color coded gold), through the sheath (color coded purple), and into the ionosphere (color coded light blue).

5.2 Foreshock ULF waves steepen and coalesce to form the quasi-parallel bow shock and magnetosheath

As the *Venus Express* approached the bow shock, the ULF foreshock waves “steepened”, increasing in amplitude, exactly as is expected in planetary foreshocks (Mann, Luehr, & Baumjohann, 1994). As the amplitude of a wave increases, its phase speed also increases (Omidi & Winske, 1990). Thus, while they are still being blown backwards towards the planet by the solar wind, these steepened waves can begin to make headway against the flow and their velocity with respect to the planet decreases. These waves pile-up and coalesce together to form the complex three-dimensional patchwork of the quasi-parallel shock and magnetosheath, as has been reported extensively at Earth, (Lucek, Horbury, Dandouras, & Rème, 2008; Schwartz & Burgess, 1991) and at Mars (G. Collinson et al., 2018), and also at Venus (G. A. Collinson, Wilson, et al., 2012; Luhmann, Russell, Phillips, & Barnes, 1987; Shan et al., 2014).

5.3 Collision of the ULF waves with the ionopause - minimal apparent effect on the Venusian ionosphere

Recent observations at Mars by *MAVEN* have shown that steepened ULF waves originating in the solar wind can rain down upon the Martian ionosphere like waves breaking on a shoreline, and that the impact of these ULF waves can drive a global compression of the entire Martian ionosphere (G. Collinson et al., 2018). As the waves break upon the Martian ionopause, compressional electromagnetic waves are excited within the Martian ionosphere, heating and energizing ionospheric plasmas, and enhancing ionospheric

escape (Fowler et al., 2018). Thus, a reasonable question to ask is: does a similar process occur at Venus?

As shown in Figure 9, *Venus Express* crossed the Venusian ionopause at approximately 08:30 GMT, descending through the sheath and into the upper ionosphere. Over the next two minutes, very weak enhancements in magnetic field magnitude ($|B|$) and electron flux were observed, possibly consistent with compressive waves in the upper ionosphere, as was observed at Mars by *MAVEN* under similar conditions (G. Collinson et al., 2018). However, the Venusian ionosphere is highly turbulent and dynamic, and these perturbations were so modest that it is quite subjective as to whether they really are the signatures of ULF waves being driven within the ionosphere, or simply normal background fluctuations. Thus, all that can be stated with certainty is that if ULF waves in the foreshock do penetrate and compress the ionosphere of Venus, it appears to be a relatively weak and subtle effect, even under the near-perfect conditions of the 13th of September 2010.

One possible explanation for this weaker effect at Venus is that its ionosphere is much thicker and “harder” than at Mars. Steepened ULF foreshock waves are comparable at both Venus and Mars, and thus the amount of force that they impart when striking their ionospheres will also be comparable. However, the ionosphere of Venus has orders of greater mass to resist the impact of foreshock waves, and thus while at Mars the collision results in a global compression of the rarified ionosphere, at Venus the waves are more easily damped and the effect is far weaker.

6 Discussion and Conclusions

6.1 Foreshock cavities are a universal phenomenon

Section 2 presented case studies consistent with foreshock cavities upstream of three terrestrial planets; Earth (Sibeck et al., 2002); Venus (sec. 2.2); and Mars (sec. 2.3). All three exhibited similar properties. Inside the cavity, the interplanetary magnetic field is weak and turbulent, solar wind densities are lower, and superthermal ion temperatures are elevated. In the bounding foreshock compressional boundaries, magnetic field strength ($|B|$) and plasma densities are enhanced, whereas plasma temperatures are not substantially different than in the solar wind. These results support the Omidi et al. (2017) 3D hybrid models of the foreshock of Venus, which predicted the existence of an Earth-like

foreshock cavity. Given that foreshock cavities have now been identified at three planets, we conclude that foreshock cavities are a universal phenomena, occurring upstream of every celestial bow shock.

6.2 Foreshock cavities have similar properties at Venus and Earth

Section 3, presented results from a preliminary survey of 15 likely foreshock cavity candidates at Venus, as encountered by the ESA *Venus Express* orbiter. Foreshock cavities appear to be common at Venus. Although we cannot establish a statistically meaningful occurrence rate, it appears to be at least once every 48 hours, and probably far more frequent. As shown by the survey results Venusian cavities have a duration of a few minutes, similar to their terrestrial counterparts. As at Earth, cavities are observed during faster than average solar wind velocities. In the bounding foreshock compressional boundaries (FCB), the magnetic field was 1.4 times stronger than in the surrounding foreshock, also consistent with observations of cavities at Earth by the *IMP-8* and *CLUSTER* missions. This similarity suggests a common physical process is occurring at all three planets, and that similar ion perturbations are present at Venus, even through they could not be resolved by the *Venus Express*.

6.3 “Foreshock cavities” are transient encounters by a spacecraft with a planetary foreshock

Section 4 examined our collected observations of cavities at Mars and Venus and compared them to a 3D hybrid simulation of the Venusian foreshock from a companion paper, Omid et al. (2020). These data and simulations strongly suggest that cavities are typical components of any magnetosphere, either induced (Venus, Mars) or intrinsic (Earth). For all encounters with cavities, the local IMF remained in contact with the bow shock, where back-streaming solar wind protons are reflected from the bow shock. The result, as suggested by Omid et al. (2009); Omid, Zhang, et al. (2013) is the creation of a region full of waves, heated diffuse plasma (the foreshock cavity), bounded by regions of higher density plasma and slightly enhanced magnetic field (the foreshock compressional boundaries).

Foreshock cavities were preferentially observed during “radial” interplanetary magnetic field (i.e. closely aligned with the Sun-Venus line). This may be a formation require-

ment, since the more radial the IMF, the longer any given field line will be in contact with the bow shock. However, it could be that “radial” conditions simply produce the most obvious and clear-cut examples of cavities that are readily spotted in a survey of spacecraft data, and at other times while the foreshock cavity is present, it is less distinct when compared to the already turbulent and complex environment upstream of a bow shock. We posit that foreshock cavities represent one of the following two possibilities: **(1.)** A spacecraft encountering a traveling foreshock formed by a finite bundle of interplanetary magnetic field lines connecting to a shock, or **(2.)** the transient temporary motion of the foreshock over the spacecraft.

Our collected observations support the hypothesis that “Foreshock Cavities” are simply the manifestations of a brief encounter by a spacecraft with a planetary foreshock, and all this entails (e.g. bounding foreshock compressional boundaries, ultra low frequency waves, et cetera).

6.4 The impact of foreshock cavities on the ionosphere may depend on the thickness of their ionospheres

At Mars, steepened ultra-low frequency waves originating in the solar wind collide with the induced magnetosphere, compressing the ionosphere (G. Collinson et al., 2018), and enhancing ionospheric escape (Fowler et al., 2018). In section 5 we examined *Venus Express* observations during passage through a stable and quasi-static foreshock cavity, finding it to be consistent in physical properties and size with the transient examples, and permitting examination of the effect of the cavity on the unprotected Venusian ionosphere. We found possible observational evidence that the impact of the steepened ULF waves in the foreshock were driving compressive waves within the upper Venusian ionosphere. However, unlike at Mars, the signatures were very modest, and thus we find that even under perfect conditions to observe the effect of foreshock cavities on the Venusian ionosphere, if present, was very weak.

With only a single case study, we must be cautious in our conclusions. However, we posit that the thicker Venusian ionosphere is far more resistant to the impact of foreshock waves than the diffuse ionosphere of Mars, and thus it is reasonable to expect that the effect on the ionosphere would be weaker at Venus than at Mars. Ideally, multi-point observations would be needed to thoroughly investigate the penetration of ULF waves

from the foreshock and into the ionosphere, with one spacecraft upstream measuring the incoming ULF wave, and the other below in the ionosphere simultaneously measuring the effect.

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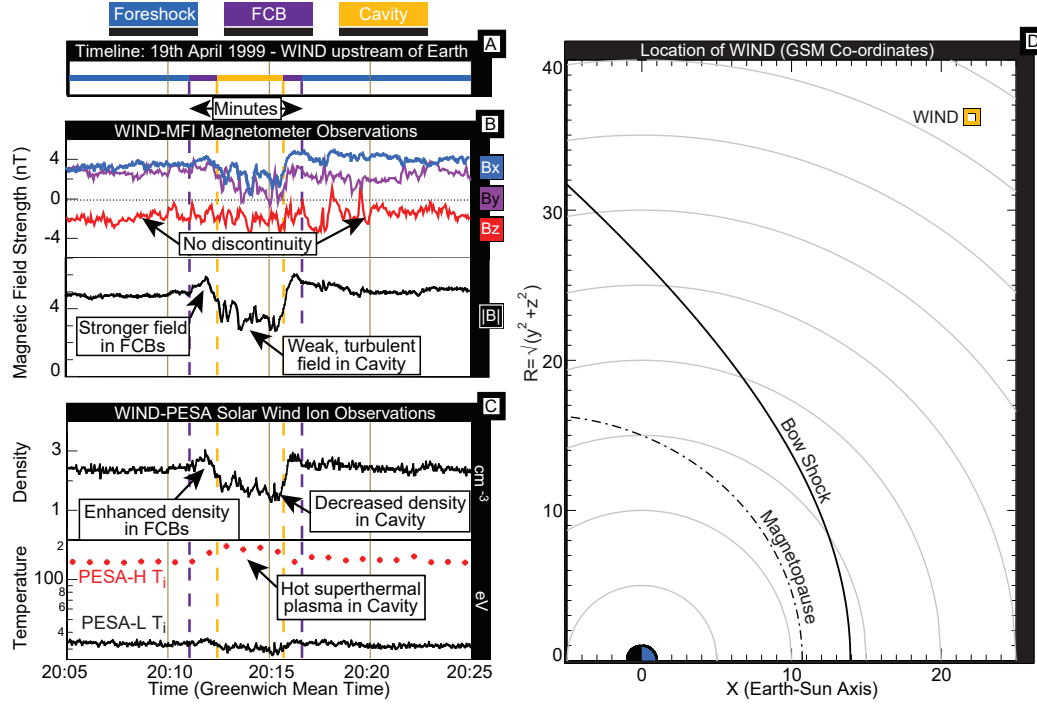


Figure 1. A Foreshock Cavity at the Earth. A foreshock cavity at Earth was reported by Sibeck et al. (2002) using data from the *Wind* spacecraft. Panel A shows boundary locations, where blue is marked for the foreshock, purple shows the location of the foreshock cavity boundary (FCB), and yellow the cavity itself. Panel B shows the IMF magnetic field components at the top and the total IMF magnetic field at the bottom. Panel C shows the density at the top and temperature at the bottom of the ion distribution. Panel D shows the location of *Wind*. Features to note are included as text boxes in the panels.

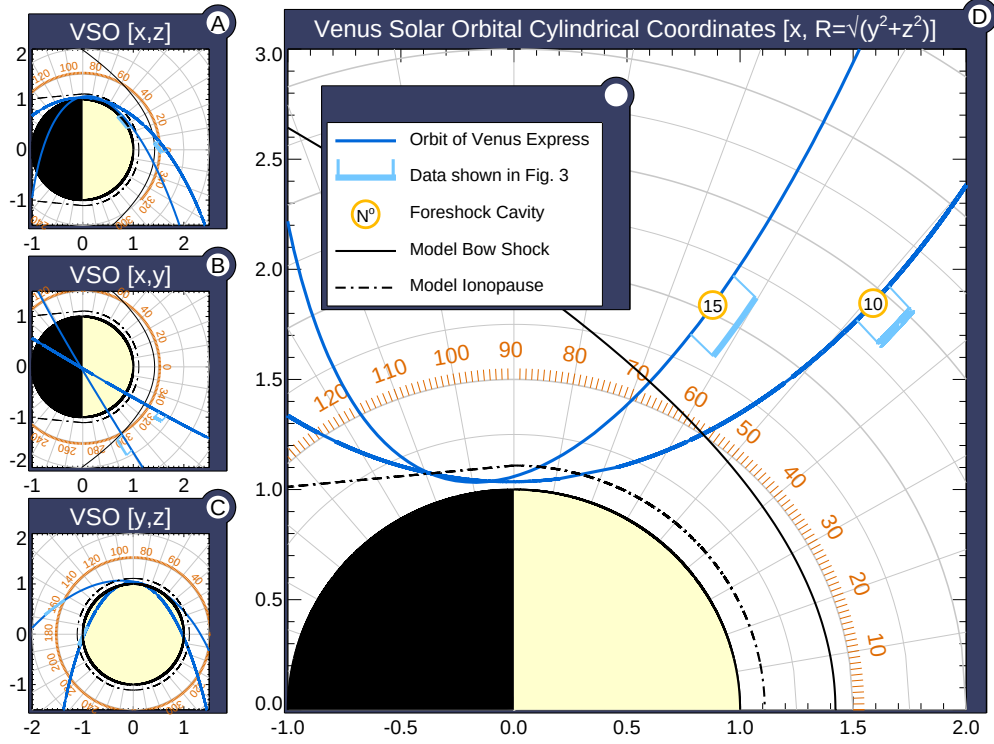


Figure 2. Map of Venusian induced magnetosphere in cylindrical VSO co-ordinates showing two orbits of the ESA *Venus Express* upon which our two case studies of foreshock cavities were encountered. Main panel D shows a cylindrical co-ordinate system whereby the x-axis points towards the sun, and the R-axis is the radial distance from this line. Overplotted are a best-fit of the Venusian bow shock from NASA *Pioneer Venus Orbiter* data by (Slavin et al., 1980a). Light-blue lines show the region from which data is shown in Figure 3

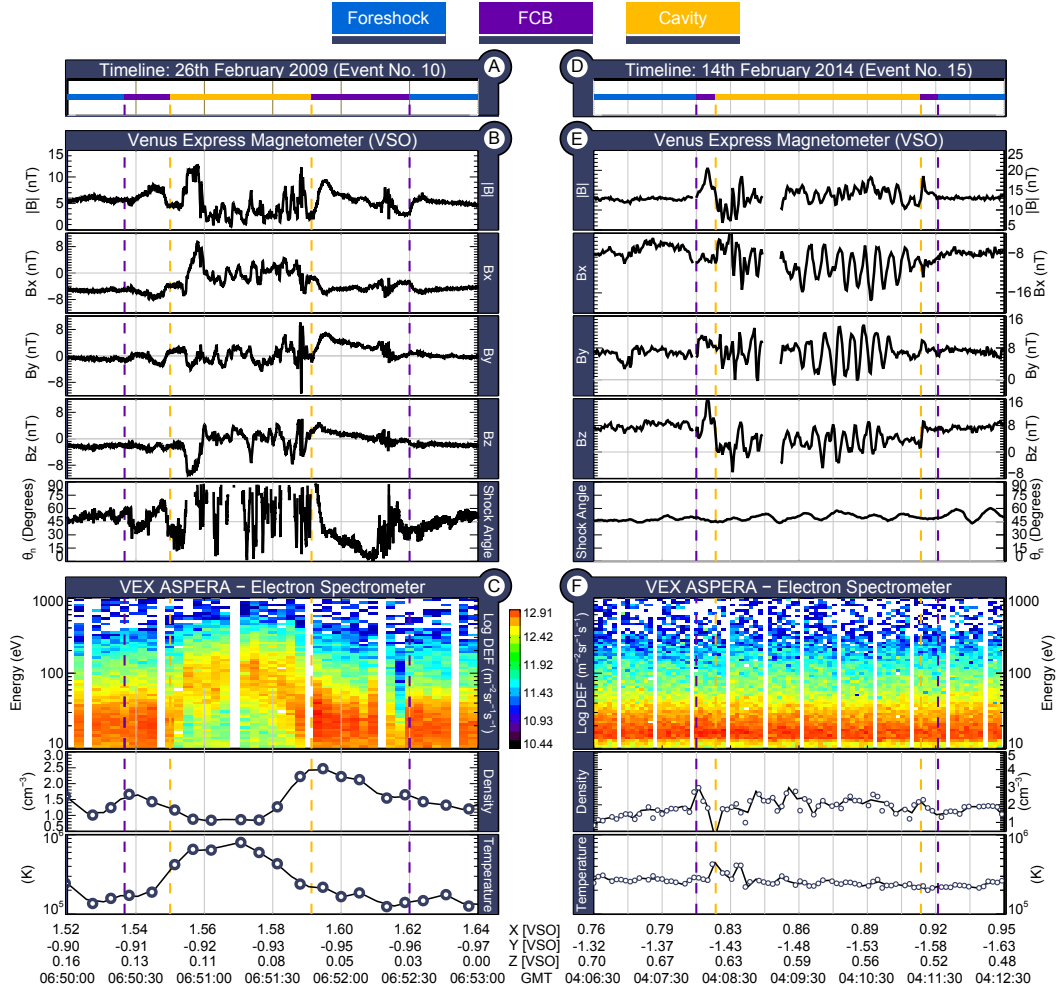


Figure 3. Two examples of foreshock cavities at Venus encountered by the ESA *Venus Express*; a shorter event previously mis-characterized as a Hot Flow Anomaly by (G. A. Collinson et al., 2014) (A-C); and a longer event consistent with flight through a quasi-stable structure (D-F). Panels A and D show a color coded timeline of each event. Panels B and E show magnetic observations by the *Venus Express* magnetometer in VSO coordinates. Panels C and F show superthermal electron measurements by ASPERA-4 ELS. Panels A and D shows the boundary locations, where blue is marked for the foreshock, purple shows the location of the foreshock cavity boundary (FCB), and yellow the cavity itself. Panels B and E shows the total IMF magnetic field at the top, magnetic field components next, followed by the angle between the magnetic field connection to the bow shock at the bottom. Panels C and F show the isotropic electron energy flux at the top followed by the electron density and electron temperature moments at the bottom (see notes in text). At the bottom of the columns marks the spacecraft VSO position and time.

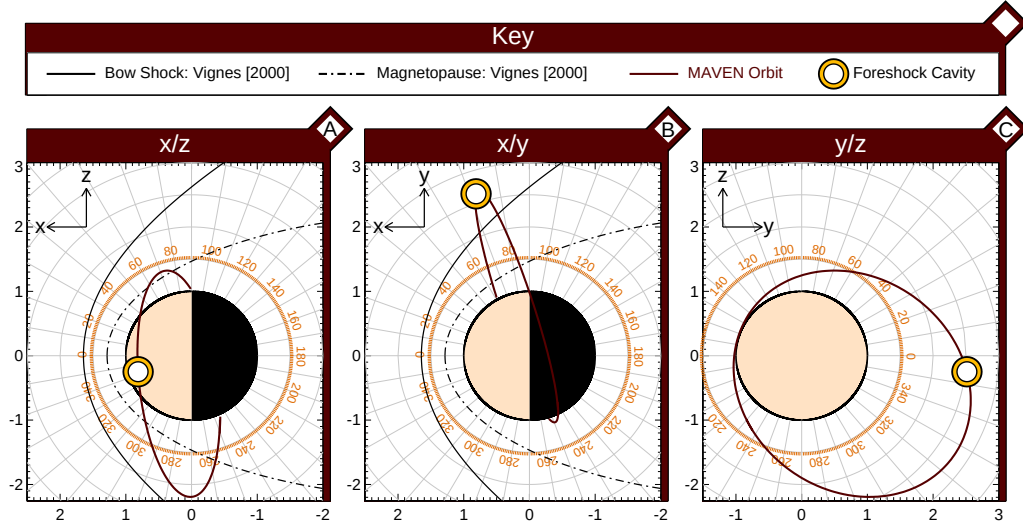


Figure 4. Map of Martian induced magnetosphere in MSO co-ordinates showing the orbit of *MAVEN*, mean bow shock and magnetopause locations according to (Vignes et al., 2000), and the location of the foreshock cavity candidate show in Figure 5. Panel A is the event timeline, panel B magnetic conditions, panel C the ion measurements, and panel D are the electron measurements (see text for detail). At the bottom of the figure is shown the spacecraft position in MSO and the time.

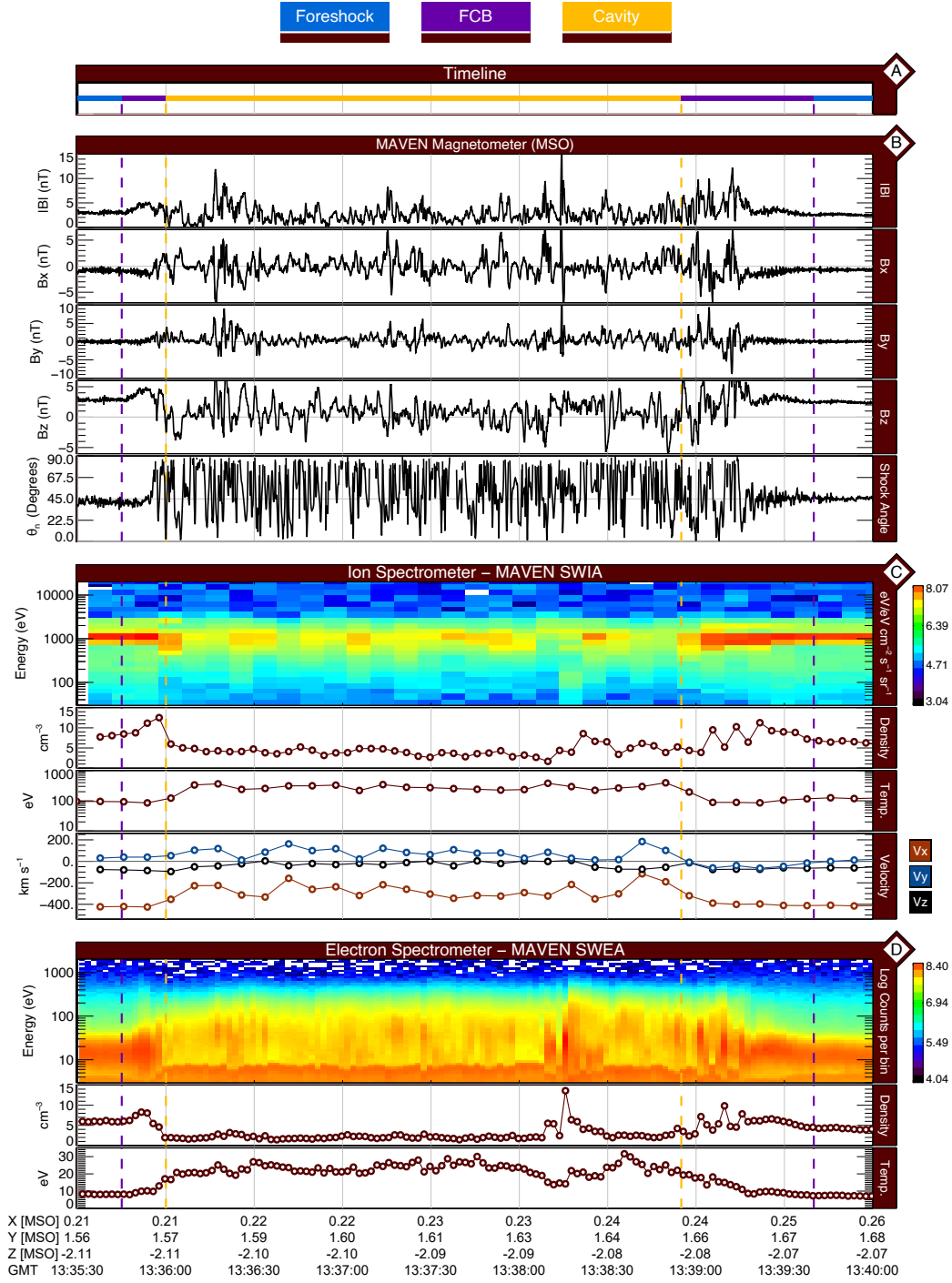


Figure 5. A Foreshock cavity encountered at Mars by NASA's *MAVEN* spacecraft, consistent with those at Earth. Panel A shows a timeline of the encounter, Panel B shows magnetic observations by the *MAVEN* Magnetometer, Panel C shows ion energy spectra, density, temperature, and velocity measurements by SWIA, Panel D shows electron spectra, density, and temperature measurements by SWEA.

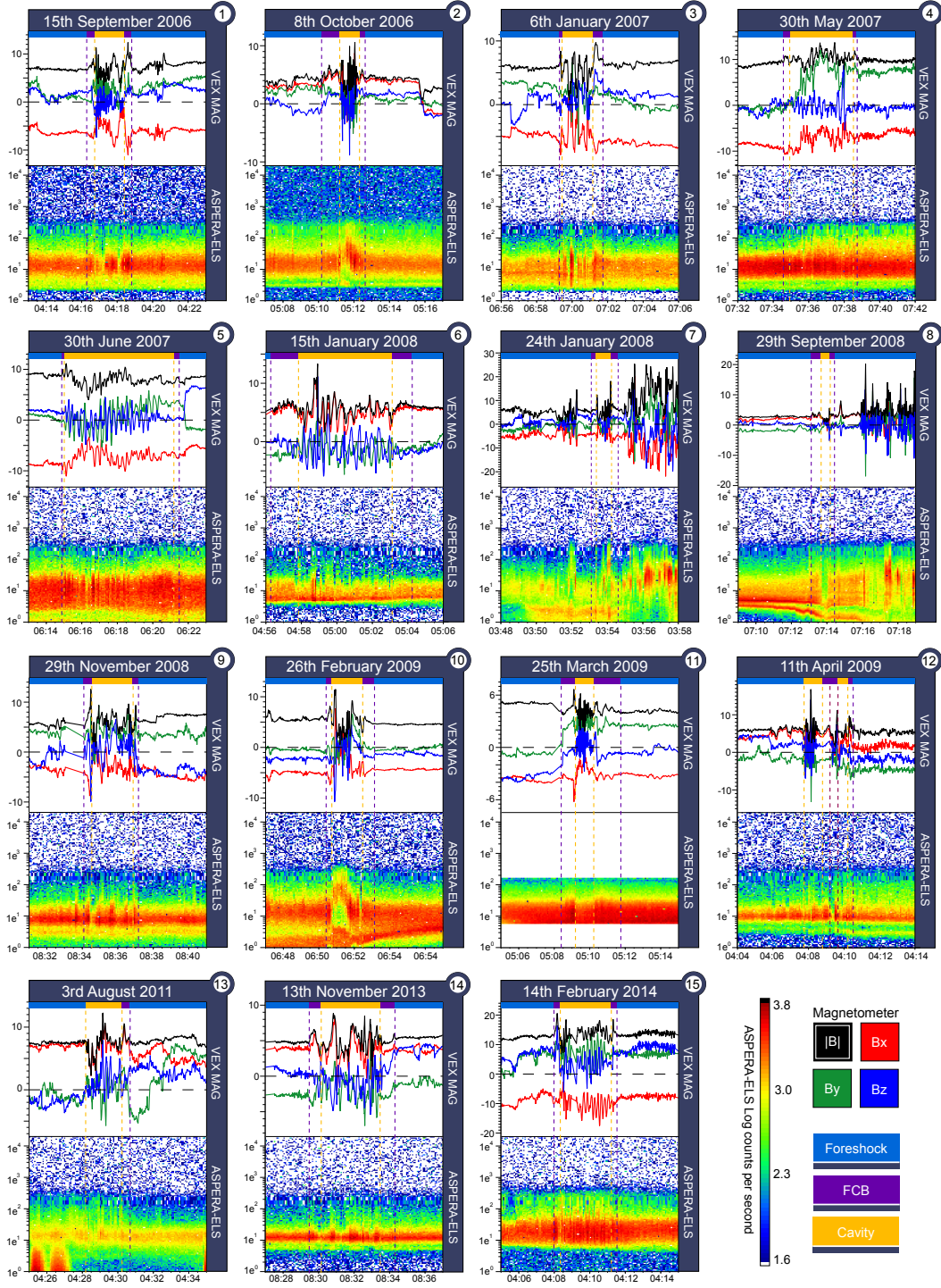


Figure 6. Magnetic field and time-energy electron spectrograms of foreshock cavity candidates at Venus. All events show 10 minutes worth of data so that the relative durations of each can be easily observed. Each panel contains the timeline at the top color coded by the scale at the lower right (see text for details). In the center of each panel are the IMF measurements in nT, color coded with the scale at the lower right. Energy-time spectrograms are shown at the bottom of each panel with energy in eV and the color scale shown at the bottom right.

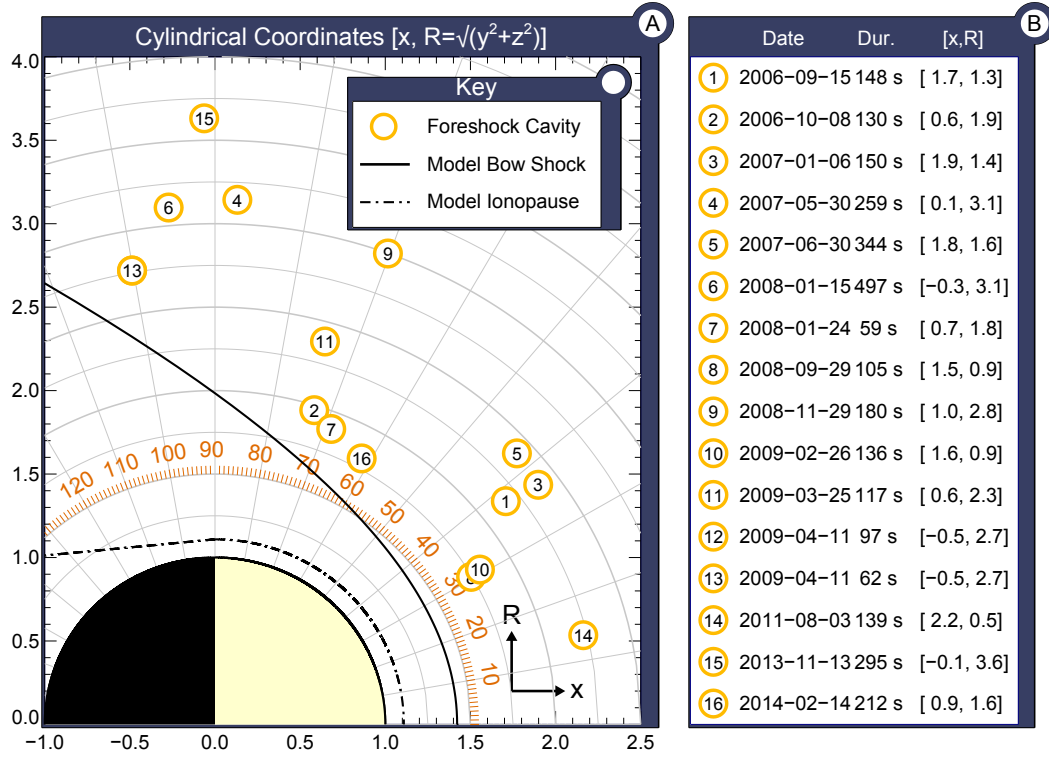


Figure 7. A.) Map of foreshock cavity candidates encountered at Venus in VSO co-ordinates;
B.) Table of events, showing date, duration, and location in VSO co-ordinates

Event	Date	Duration	IMF Strength & Angles						Solar Wind Ions					
№		(s)	B (nT)		ΔB / B (nT)	θ _{IMF} (°)		φ _{IMF} (°)		Θ _{$\hat{B}, \hat{n}$} (°)		n _{SW} (cm ⁻³)	V _{SW} (km/s)	
			Pre	Post		FCB	$\frac{Foreshock}{cavity}$	Pre	Post	Pre	Post			Pre
1	2006-09-15	148	6.7	7.0	1.2	1.4	-8.0	-23.2	11.0	14.0	30.3	16.6	10.0	551
2	2006-10-08	130	4.4	4.4	1.2	0.9	37.0	11.6	-14.8	22.2	85.6	69.9	6.1	412
3	2007-01-06	150	5.6	6.2	1.2	1.4	-30.7	-3.0	9.5	15.4	34.1	41.8	5.7	506
4	2007-05-30	259	8.7	9.5	1.2	1.4	4.5	-48.2	-4.4	-3.2	67.6	12.4	3.3	548
5	2007-06-30	344	8.8	7.5	1.1	1.3	-7.8	-25.9	12.2	1.9	60.6	83.8	7.2	424
6	2008-01-15	497	3.8	5.7	1.2	0.8	-21.4	-0.8	28.6	-12.7	34.2	61.9	0.6	528
7	2008-01-24	59	5.5	6.0	1.4	1.6	1.6	-13.1	38.3	25.0	51.5	60.5	3.7	492
8	2008-09-29	105	2.7	3.2	1.2	0.8	-34.0	-7.2	5.4	-10.3	61.6	45.1	8.3	329
9	2008-11-29	180	5.4	6.7	1.5	2.3	-44.6	-39.9	0.6	-38.3	22.4	24.6	1.8	362
10	2009-02-26	136	5.5	4.7	1.2	1.5	6.1	4.8	-23.8	-18.0	40.7	43.1	4.7	376
11	2009-03-25	117	4.3	4.1	1.2	2.3	-35.2	-39.4	-7.6	-9.4	30.7	29.6	6.9	407
12	2009-04-11	97	6.0	4.2	1.7	0.9	-17.9	-47.3	19.8	9.8	37.4	28.0	4.9	486
13	2011-08-03	139	7.5	7.2	1.2	1.0	-8.9	-17.5	-14.4	28.6	20.7	49.0	4.9	622
14	2013-11-13	295	4.8	5.4	1.1	1.1	-34.6	-17.2	6.4	46.5	16.3	37.2	1.7	442
15	2014-02-14	212	12.6	13.5	1.3	1.5	-40.6	-41.7	37.1	40.0	57.3	57.2	11.2	399
Typical (<i>IMF</i> _☉ , <i>SW</i> _☉ , <i>FC</i> _⊕)			90-180s _⊕ [†]	6.99 nT _☉ [†]	-	1.1 [*] _⊕ →1.7 [‡] _⊕	-2.06° _☉ [†]	-42.16° _☉ [†]	-	-	-	-	4.19 _☉ [†]	361.5 _☉ [†]
Mean (<i>FC</i> _☉)			191s± 115s	6.2± 2.5 nT	1.3± 0.1	1.4± 0.5	-18.1± 20.9°	7.2 ± 20.9°	43.7± 20.9°	43.7± 20.0°	5.4± 3.0	459 ± 82	-	-
Change (Post-Pre)			-	0.20(Δ <i>nT</i>)	-	-	-4.89 (Δ°)	0.49 (Δ°)	0.64 (Δ°)	-	-	-	-	-

Table 1. Properties of 15 Venusian foreshock cavity candidates compared against typical properties at Earth (⊕) according to Billingham et al. (2008)[†] Sibecket al. (1989)^{*}. Attendant conditions in the interplanetary magnetic field (IMF) and solar wind, compared against mean ($|\bar{B}|$, $\bar{n}_{SW}$, $\bar{V}_{SW}$) and mode (θ_{IMF} , ϕ_{IMF})conditions at Venus (♀) according to Collinson et al. (2015)[†].

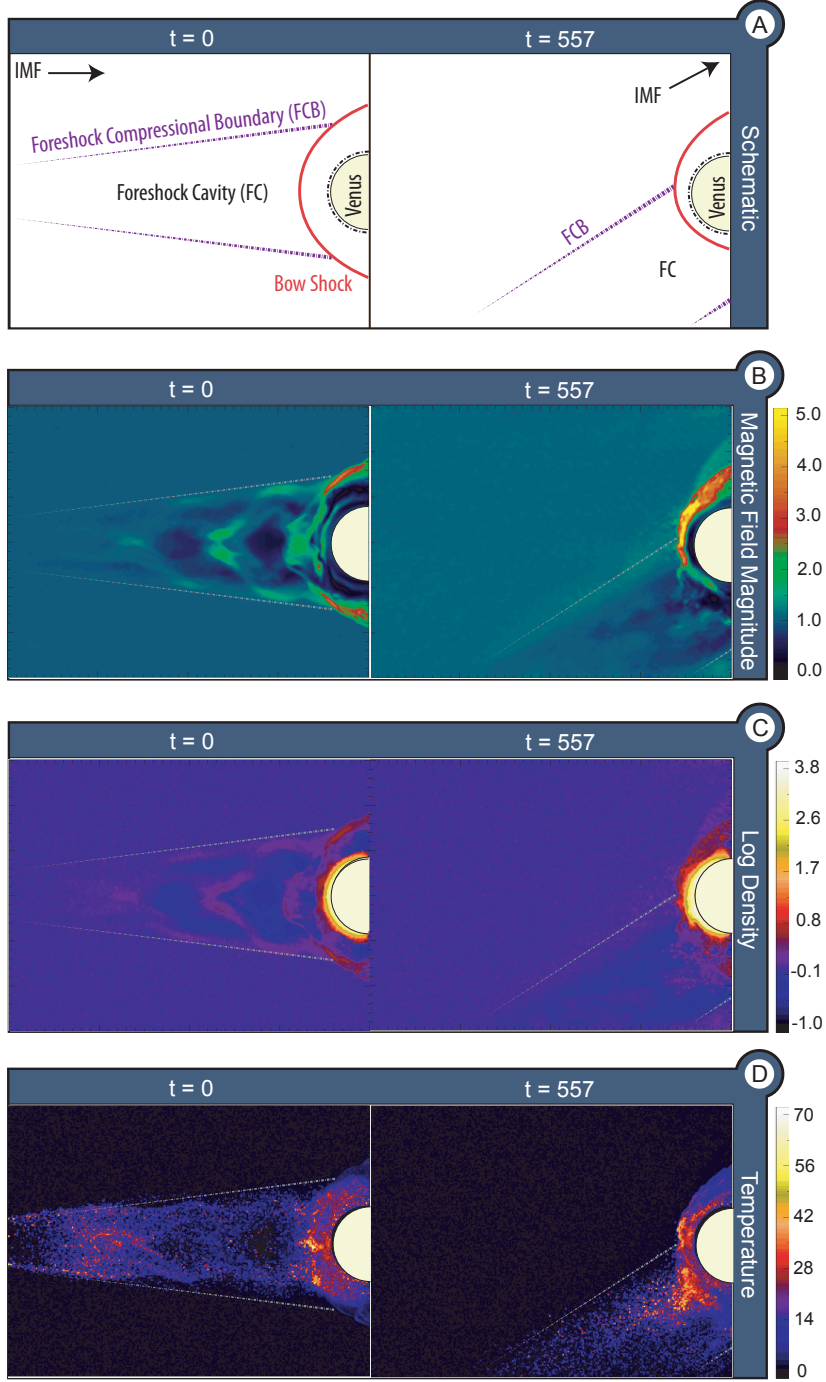


Figure 8. Hybrid simulations of the foreshock of Venus, showing the formation of the foreshock cavity under radial and typical IMF cone angles. Panel A is a labeled schematic of the simulation, panel B is the magnetic field magnitude, panel C is the plasma density and panel D is the plasma temperature. Left to right show snapshots of the simulation before and after the IMF discontinuity (see text for details).

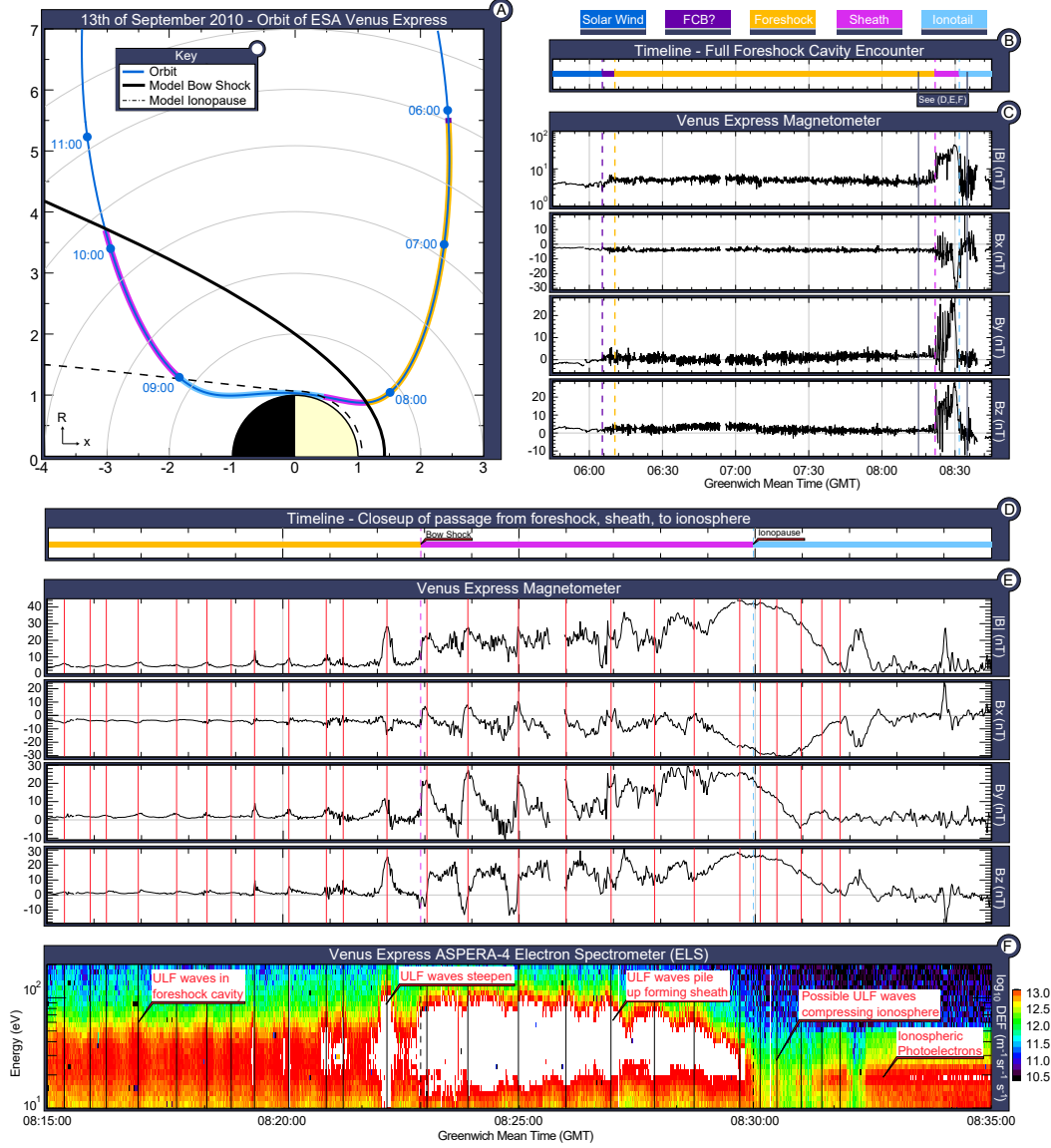


Figure 9. *Venus Express* observations of the foreshock of Venus under stable “radial” IMF conditions reveal the extent of the foreshock cavity and its impact on the ionosphere. Panel A shows a map of the orbit of the ESA *Venus Express*. Panel C shows magnetic observations covering the three hours prior to periapsis over the Venusian north pole, with panel B showing the associated timeline. Panels D, E, F, show a close-up of 20 minutes of magnetic and electron observations covering the period when the *Venus Express* flew from the foreshock, through the bow shock into the sheath, and finally through the ionopause into the ionosphere and out into the ionotail. The crests of ultra-low frequency (ULF) waves are highlighted in red on panels E, F. The z-axis (electron flux) of panel F is cut-off at $1 \times 10^{13} \text{ m}^{-1} \text{ sr}^{-1} \text{ s}^{-1}$ so that the enhancements due to the compressional waves may be better seen, with areas in white on panel F being off-scale high.