# Hot flow anomalies at Venus

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[1]  We present a multi-instrument study of a hot flow anomaly (HFA) observed by the Venus Express spacecraft in the Venusian foreshock, on 22 March 2008, incorporating both Venus Express Magnetometer and Analyzer of Space Plasmas and Energetic Atoms (ASPERA) plasma observations. Centered on an interplanetary magnetic field discontinuity with inward convective motional electric fields on both sides, with a decreased core field strength, ion observations consistent with a flow deflection, and bounded by compressive heated edges, the properties of this event are consistent with those of HFAs observed at other planets within the solar system.

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## 1.  Introduction

[2]  Hot flow anomalies (HFAs) are explosive plasma phenomenon thought to form when certain discontinuities in the interplanetary magnetic field (IMF) interact with a planetary bow shock [*Thomsen et al.*, 1993; *Schwartz*, 1995; *Schwartz et al.*, 2000]. HFAs were discovered in the solar wind just sunward of Earth's bow shock, by Active Magnetospheric Particle Tracer Explorers (AMPTE) [*Schwartz et al.*, 1985] and International Sun-Earth Explorer (ISEE) [*Thomsen et al.*, 1986]. These spacecraft encountered regions of strongly deflected hot plasma with bulk velocities much slower than those of the solar wind, in which measurements of the magnetic field dropped precipitously in magnitude and displayed significant fluctuations [*Tjulin et al.*, 2008]. Strong compression regions with denser and hotter plasma and enhanced magnetic field strengths bounded the central region on one or both sides. The events were initially referred to as "active current sheets," or "hot diamagnetic cavities" before the community finally settled on the phenomenological term "hot flow anomaly" [*Paschmann et al.*, 1988; *Thomsen et al.*, 1988; *Schwartz et al.*, 1988]. These events, which occur at a rate of about 1 d$^{-1}$ [*Schwartz et al.*, 2000] have been studied extensively at Earth by missions such as Interball [*Vaisberg et al.*, 1999], Cluster [*Facskó*

et al., 2009; *Lucek et al.*, 2004], and Time History of Events and Macroscale Interactions during Substorms (THEMIS) [*Eastwood et al.*, 2008; *Zhang et al.*, 2010].

[3]  Despite being localized foreshock phenomena that last for only a few minutes, HFAs are important at Earth because they can have dramatic global effects on the entire magnetosphere, and even on the ionosphere [*Sibeck et al.*, 1998]. The large fluctuations in magnetic pressure associated with an HFA drive large variations in the motion and location of the magnetopause. This is observable as transient magnetic field deflections [*Eastwood et al.*, 2008], and auroral brightenings [*Sibeck et al.*, 1999]. HFAs are therefore a fundamental mode of interaction between the solar wind and Earth and are likely to be found at other planets in the solar system and in astrophysical space plasma environments wherever collisionless shocks and current sheets can interact.

[4]  While HFAs have been thoroughly studied at Earth, comparatively few have been observed elsewhere in the solar system. This is largely because they are highly transient and localized events. The orbits of interplanetary spacecraft are often a compromise between the requirements of different scientific disciplines and therefore are not optimized for the study of the foreshock, the only region where it is even theoretically possible to observe an extraterrestrial HFA.

[5]  The first such possible observation at another planet was reported by *Øieroset et al.* [2001], after Mars Global Surveyor observed a "hot diamagnetic cavity" upstream of the Martian foreshock. They reported a transient encounter with a region of hot electron plasma flanked by layers of enhanced magnetic field and electron density, accompanied by a rotation of the IMF, that they concluded to potentially be the Martian equivalent of an HFA. This was an exciting discovery, since it suggested that HFA formation may be independent of whether the obstacle is a planetary atmosphere or magnetosphere: all that is required is that there be an obstacle in a supersonic plasma flow to generate a shock, and for a discontinuity to interact with it. However, the *Øieroset et al.* [2001] study had only electron measurements

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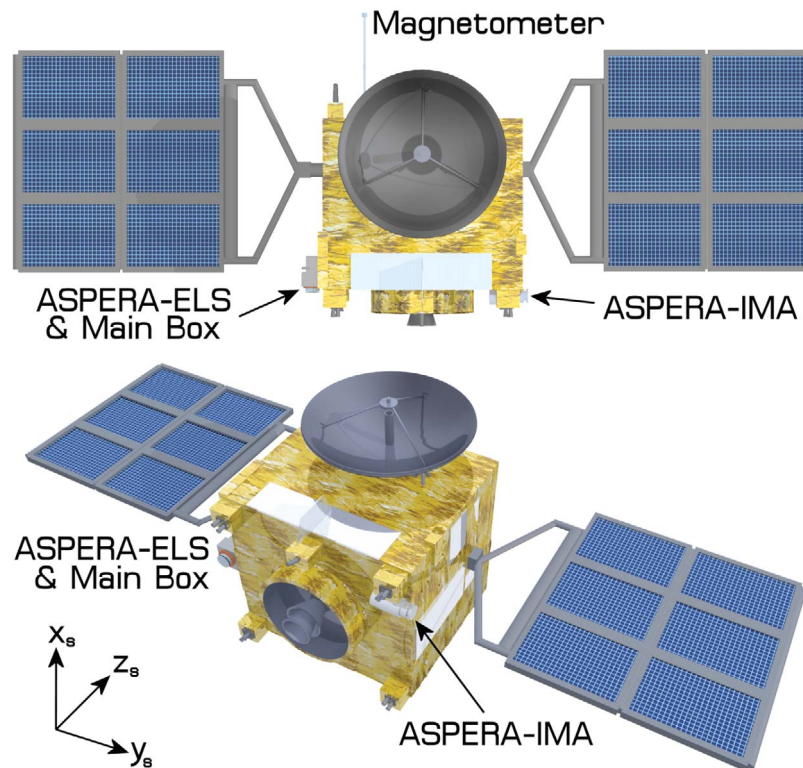[7]Swedish Institute of Space Physics, Kiruna, Sweden.

**Figure 1.** A 3-D model of the Venus Express, showing the mounting positions of the magnetometer, ASPERA-ELS, and ASPERA-IMA.

to work with, and were unable to provide evidence for a flow deflection. Therefore, they were unable to unambiguously prove the existence of HFAs at an unmagnetized body.

[6] More recently, Kronian HFAs were hypothesized [*Masters et al.*, 2008] and have been subsequently confirmed [*Masters et al.*, 2009] with observations by Cassini. They reported the first unambiguous evidence of plasma heating and deflection (unlike the Martian events), and thus were able to show that HFAs are truly a solar system wide phenomenon, and by proving that they can occur over a great range of heliospheric distances, from 1 to 10 astronomical units.

[7] The first (and so far only) observations of an HFA-like event at Venus were reported by *Slavin et al.* [2009]. On 5 June 2007, the Mercury-bound NASA Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) spacecraft [*Solomon et al.*, 2001] encountered Venus to perform the second of two gravitational assist maneuvers. This brief encounter permitted a rare opportunity to perform multispacecraft observations of the Venusian system, with the orbiting European Venus Express [*Svedhem et al.*, 2007] acting as an upstream solar wind monitor.

[8] During the encounter, the magnetometer aboard MESSENGER recorded two events with magnetic signatures indicative of two possible hot flow anomalies. However, HFAs are fundamentally plasma, not magnetic, phenomena, and without reliable plasma measurements *Slavin et al.* [2009] were unable to demonstrate unambiguous signatures of the heating or deflection of plasma that would demonstrate the occurrence of Venusian HFAs. In particular, the second of the two reported MESSENGER

HFA-like signatures exhibits a magnetic field magnitude and orientation very similar to those of a bow shock crossing only 75 s later. Without plasma measurements, this second event might also be interpreted as a transient encounter with the Venusian bow shock.

[9] In this paper, we present Venus Express magnetic, electron, and ion measurements from 22 March consistent with an HFA. Our observations of plasma perturbations combined with a magnetic signature similar to the first HFA-like event observed by MESSENGER allow us to confirm the occurrence of Venusian HFAs postulated by *Slavin et al.* [2009]. Finally, we briefly discuss the possible implications of an HFA on the induced magnetosphere of Venus.

[10] This paper is arranged as follows. In section 2 we describe the instrumentation used in this study. In section 3 we assess the known formation conditions of an HFA. In section 4 we present a case study of a Venusian HFA observed on 22 March 2008. Finally, in section 5 we summarize and discuss what effects an HFA might have on the Venusian system.

## 2. Instrumentation Used to Observe a Venusian HFA

[11] Here we present a brief overview of the three instruments aboard the Venus Express used for this study and explain key features of their operation which are required for the interpretation their respective data sets. Figure 1 shows a 3-D model of the Venus Express and the mounting positions of these instruments.
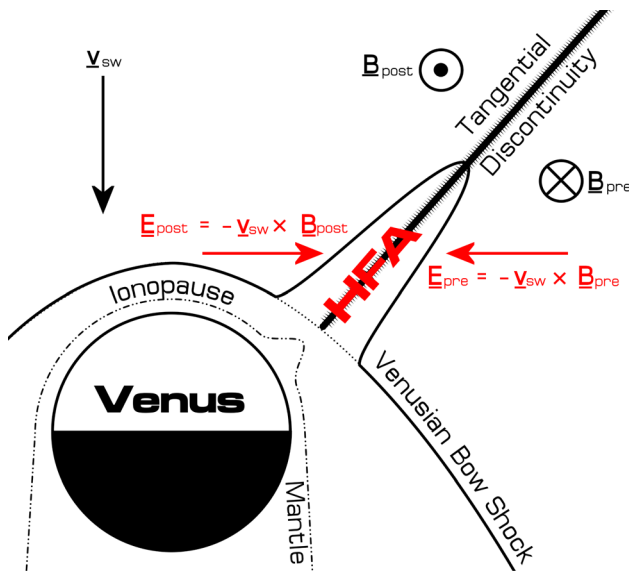
**Figure 2.** Schematic of the formation conditions of a hot flow anomaly at Venus, based on a *Schwartz et al.* [2000] diagram for Earth and on the findings of this study.

[12] The Venus Express is a three-axis stabilized spacecraft equipped with an array of modern space plasma instrumentation that make her far better equipped to study Venusian plasma phenomena such as HFAs than any previous mission to Venus. In particular, she carries both an electron spectrometer (ELS) and ion mass analyzer (IMA), both of which are part of the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4) investigation [*Barabash et al.*, 2007]. Additionally, unlike her sister ship, the Mars Express, Venus Express has the good fortune to carry a magnetometer [*Zhang et al.*, 2006].

[13] Venus Express was the third in her class after Rosetta and Mars Express, and many of the components used in her construction were flight spares left over from these two missions. In particular, the electron spectrometer (ASPERA-ELS) was a spare unit never originally intended for flight, and it was known to have a sensitivity that was almost 6 times lower than expected due to misalignments of the electron optics during manufacture [*Collinson et al.*, 2009]. While the optical effects of these offsets have now been corrected for in postlaunch calibration, and the data sets presented here are reliable, the lower than desired sensitivity means that in sparsely populated regions such as under typical solar wind conditions, several time bins must be summed to obtain sufficient counting statistics to calculate moments such as electron density and temperature. Thus in this case study we have limited ourselves to observations of higher time resolution electron differential energy flux. The temporal resolution of ASPERA-ELS can be as high as 1 s per energy sweep, but for the case study presented in this paper, the temporal resolution was set at 4 s. ASPERA-ELS looks along the $x_s/y_s$ plane (see Figure 1), and has a motor that can turn it about the $y_s$ axis so that it may be turned to look along the $x_s/z_s$ plane. The instrument was stationary for the case studies presented here. These field-of-view constraints makes the construction of full 3-D velocity distributions very challenging, and we are largely reliant on the assumption of electron semi-isotropy for studies of rapid events such as HFAs.

[14] The ion mass analyzer (ASPERA-IMA) [*Barabash et al.*, 2006] is equipped with electrostatic deflector plates which allow the sensor to scan $\pm$ 45° in 16 steps. The aperture of IMA is oriented along the $x_s/z_s$ plane (see Figure 1). On 22 March 2008, IMA was operating in a mode whereby the distributions from two adjacent deflection states were summed together, so that it will scan the sky in only eight steps, thus saving telemetry. IMA has a time resolution of 196 s for a full 3-D scan, which can lead to aliasing. This makes looking for the signature of ions deflected by the ~30 s duration on 20 March 2008 HFA a matter having had the good fortune that the instrument happened to be looking in the right direction at the right time.

## 3. Assessment of HFA Formation Conditions

[15] Figure 2 illustrates our present understanding of the conditions favoring the formation of HFAs. Formation begins when a tangential discontinuity [*Hudson*, 1970] in the IMF intersects with a bow shock. The advection of the solar wind with its frozen in magnetic field creates a motional electric field pointing inward toward the discontinuity according to $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$. The electric field helps trap ions reflected and energized by their encounter with the bow shock [*Burgess*, 1989]. Simulations [*Thomas et al.*, 1991; *Omidi and Sibeck*, 2007] and spacecraft observations [*Thomsen et al.*, 1993] indicate that an apparent requirement for HFA formation is that the motional electric field is pointed toward the discontinuity on at least one side.

[16] The exact mechanism of plasma heating remains unclear. It has been postulated that ions are heated through ion-ion instabilities [*Gary*, 1991] that results in a population of hot plasma that expands along the discontinuity. Electron heating is thought to be a result of hybrid waves [*Zhang et al.*, 2010].

[17] An important requirement for Terrestrial HFA formation is that the orientation of the discontinuity is approximately parallel to the Earth-Sun line, so that the discontinuity has sufficient time to encounter the bow shock and capture the ions. We expect this to be especially true for Venus, since even though it is similar in size to our own planet [*Mitchell*, 1860], its induced magnetosphere offers a target only a tenth the size of Earth's [*Russell and Vaisberg*, 1983].

## 4. An Encounter With an HFA at Venus on 22 March 2008

[18] At approximately 03:49:00 UT on 22 March 2008, Venus Express encountered an HFA centered along a discontinuity in the interplanetary magnetic field. This event currently represents our best candidate for a Venusian hot flow anomaly. In this section we present our findings, and in particular demonstrate that this event caused plasma perturbations that are consistent with our understanding of HFAs. Data covering a close-up of the event is presented in Figure 3, and again in Figure 4, which also covers a period leading up to the event, so that the field and particle
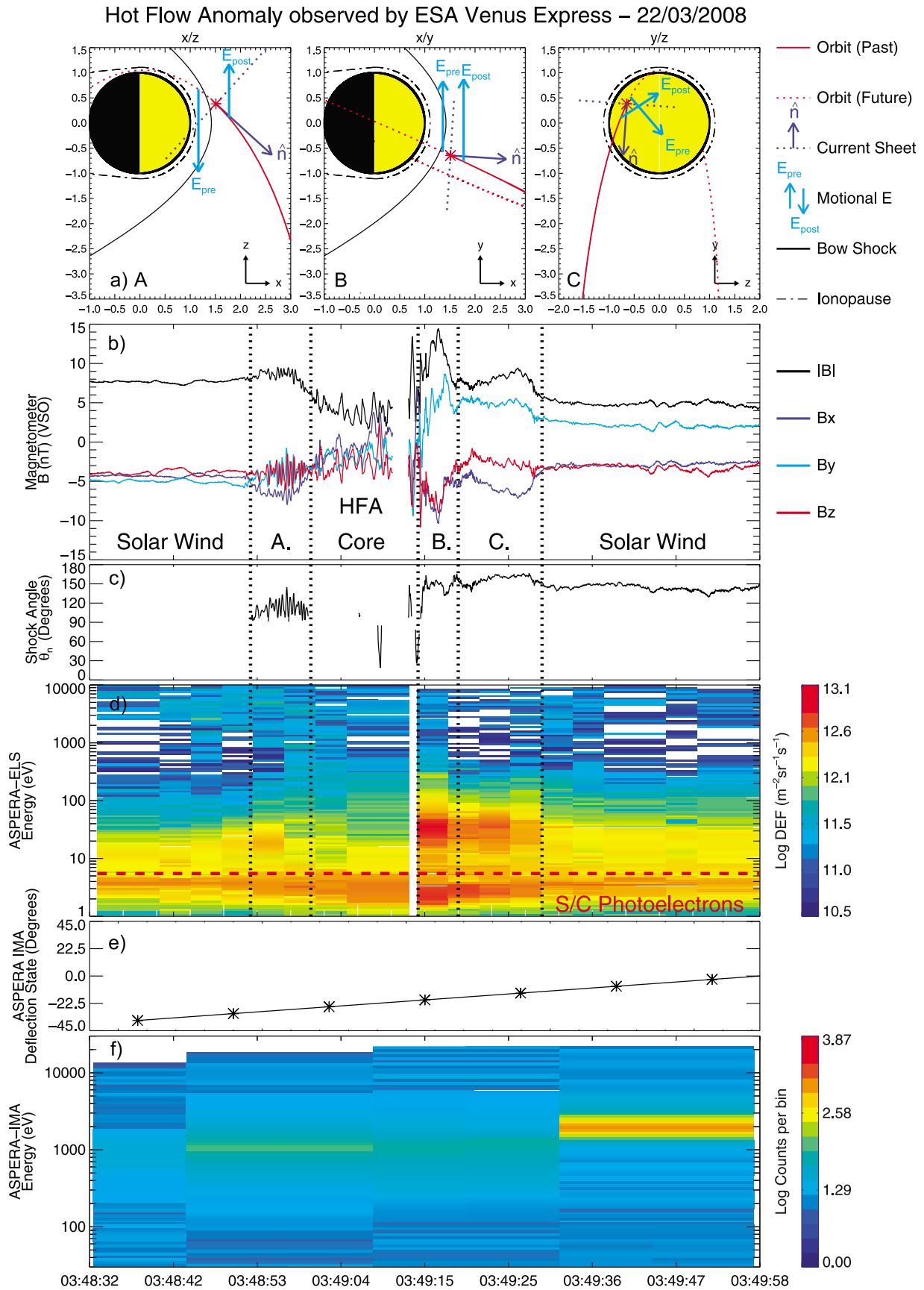
Hot Flow Anomaly observed by ESA Venus Express – 22/03/2008



**Figure 3.** A hot flow anomaly as observed by the ESA Venus Express Spacecraft. Data taken on 22 March 2008, covering the period from 03:48:32 to 03:49:58 UT.
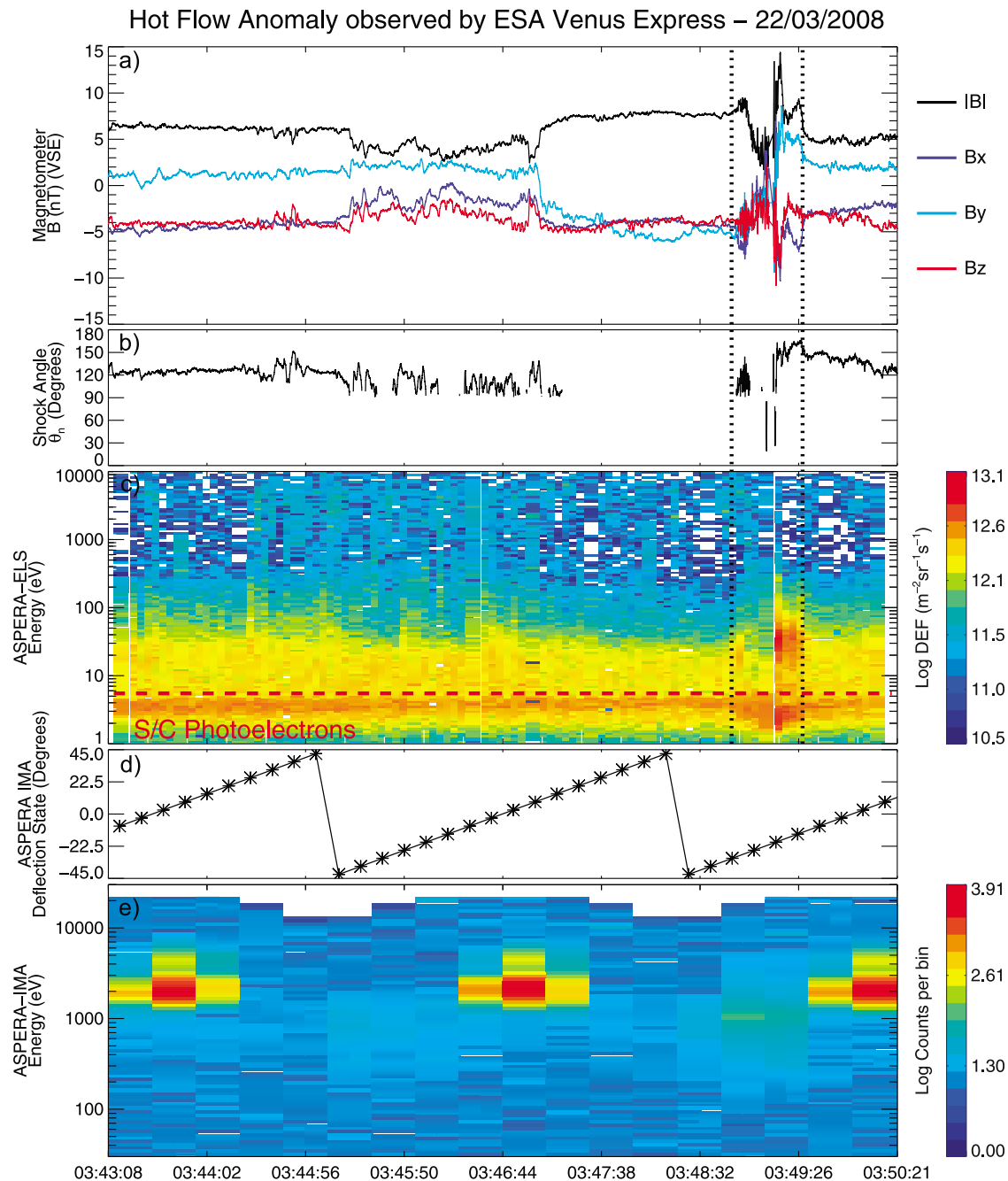
**Figure 4.** The same hot flow anomaly as in Figure 3 but with data covering a longer period from 03:43:08 to 03:49:58 UT in order that the particle and field disruptions can be more easily contrasted against normal solar wind conditions.

perturbations due to the HFA can be more easily contrasted against normal solar wind conditions.

## 4.1. Position and Orientation of Interplanetary Discontinuity

[19] Figure 3a presents to scale the position of the Venus Express along her orbital path relative to the planet and an idealized bow shock, based on the work by *Slavin et al.* [1980]. The coordinate system is Venus solar ecliptic

(VSE), where x points sunward, y points back along the orbital path of Venus, with z completing the right-hand system, pointing out of the plane of the ecliptic. The units of distance are Venus radii.

[20] We have assumed the discontinuity to be tangential, given this is the type which HFAs are thought to form around [*Schwartz et al.*, 2000]. The IMF discontinuity is denoted by a dotted blue line, with the normal vector shown by a blue arrow. This was calculated by averaging the

**Table 1.** Vector Properties of the Venusian HFA

| Property | HFA Values |
| --- | --- |
| $\hat{\bar{B}}_{pre}$ | $[-0.54, -0.64, -0.55]$ |
| $\hat{\bar{B}}_{post}$ | $[-0.59, 0.44, -0.68]$ |
| C/S normal ($\hat{n}$) | $[0.74, -0.04, -0.67]$ |
| $\theta_{\hat{\bar{B}}_{pre}.\hat{\bar{B}}_{post}}$ | $53.9°$ |
| Position | $[1.51, -0.65, 0.38]$ |
| $\theta_{\hat{n}.\bar{E}_{pre}}$ | $49.0°$ |
| $\theta_{\hat{n}.\bar{E}_{post}}$ | $-37.7°$ |

magnetic field vector before, ($\bar{\mathbf{B}}_{pre}$ from 03:47:20 to 03:48:50 UT) and after ($\bar{\mathbf{B}}_{post}$ from 03:49:30 to 03:50:00 UT) the event, and the normal vector ($\hat{n}$, dark blue arrow) for a tangential discontinuity is found by the cross product, according to [after *Hudson*, 1970]

$$\hat{\mathbf{n}} = \bar{\mathbf{B}}_{pre} \times \bar{\mathbf{B}}_{post} \qquad (1)$$

These vectors are summarized in Table 1. This discontinuity clearly intersects the bow shock of Venus and is quasi-parallel to the Sun-Venus line. Thus, we deduce that the Venus Express was in the right place, and at the right time, to observe an HFA and that the conditions of this discontinuity were consistent with our understanding of terrestrial HFA formation.

### 4.2. Field and Particle Observations

#### 4.2.1. Overview

[21] We have divided the event into five regions, as labeled on Figure 3b. We will now briefly describe our interpretation of the different regions of this event, and will then spend the rest of this section presenting the evidence from each of the three instruments which led us to these conclusions. Observations begin in the quiet solar wind upstream of the bow shock of Venus. In region A we observe what we believe to be the downstream compressive regions caused by the expansion of the HFA. Next the spacecraft encountered the core of the HFA where $|B| \Rightarrow 0$. This is followed by what we interpret as the other bounding compressive region, divided into B and C. This is the side of the event expanding against the flow of the solar wind, and thus one expects it to be more strongly compressive than the downstream region A. Finally, as the HFA passes over the spacecraft, we are returned to the quiet solar wind upstream of the bow shock.

#### 4.2.2. Magnetometer

[22] Figure 3b shows observations made at 32 samples per second resolution by the Venus Express Magnetometer. The event itself covers the period from ~03:48:53 to ~03:49:30 UT. There is a clear change in the orientation of the IMF before and after the event, largely evident in a change in $B_y$ from $-5$ to $+2$ nT. Thus, we infer that the event is centered on a discontinuity in the solar wind.

[23] While the event itself took only ~30 s to pass the spacecraft, it left a magnetic signature with all the main features of an HFA. Within the core of the event, the total magnetic field strength ($|\mathbf{B}|$) drops close to zero, which is exactly what would be expected for an HFA [*Masters et al.*, 2009]. On either side of the event, there are regions (labeled A, B, and C) where the magnetic field is stronger than in the

surrounding solar wind, as seen during terrestrial HFAs [*Thomsen et al.*, 1986]. Region A represents the side of the HFA expanding with the solar wind, and regions B and C represent the region expanding against the bulk solar wind flow. We attribute these magnetic signatures to weakly shocked plasma that is being compressed as the HFA rapidly expands into the surrounding solar wind.

[24] In region B, we observe a strong peak in the magnetic field, and a sudden increase in field strength consistent with a shock, which we attribute to the strong compressional effect of the HFA on the side that is expanding against the flow of the supersonic solar wind, as observed at Earth [*Zhang et al.*, 2010]. In region C, magnetic field strength continues to be elevated above that of the following solar wind. While we cannot authoritatively speculate on why this compressive zone is split into two distinct regions due to the paucity of data, this magnetic signature is similar to that observed by *Masters et al.* [2009].

[25] Figure 3c shows a plot of the angle that the magnetic field vector makes with the bow shock of Venus. During the event, a significant deflection (of approximately 60° to 70°) in shock angle is observed, which is again highly indicative of HFAs observed elsewhere in the solar system (e.g., *Tjulin et al.* [2008] for Earth and *Masters et al.* [2008] for Saturn).

#### 4.2.3. Electron Spectrometer

[26] Figure 3d shows data from the ASPERA-4 electron spectrometer (ELS). The approximate spacecraft potential is marked with a red dotted line, with electrons below this level likely being of spacecraft origin. In the core of the HFA, where the magnetic field strength is very low ($|\mathbf{B}| \approx 0$), one would expect a drop in electron velocity and the lowest densities and highest temperatures of the HFA. However, attempts to extract these parameters in this region were frustrated by the low sensitivity of ASPERA-ELS [*Collinson et al.*, 2009], meaning that there are insufficient counts from which to fit distributions and extract reliable moments. This is further hampered by the short time scale of this event and the data gap in the core of the HFA, meaning that successive energy bins could not be summed to improve counting statistics.

[27] The regions bounding the core (A, B, and C) exhibit higher electron flux, at higher energies, than either the HFA core or the solar wind (these deviations from normal solar wind electron distributions can more easily be compared in Figure 4c). This is consistent with our interpretation that these regions contain weakly shocked heated plasma that has been compressed by the expansion of the HFA, just as observed at Earth [*Schwartz*, 1995]. We interpret the higher flux in regions B and C, the side expanding against the solar wind flow, as compared to region A which is expanding with the solar wind flow, to be further evidence that the upstream side is more compressive than the downstream side, as has been observed at Earth [*Zhang et al.*, 2010].

[28] Region B is where ELS records the highest flux of electrons during this event. We have thus taken advantage of the improvement in counting statistics to estimate the temperature of the plasma in this region, to look for evidence of the expected electron heating. It is important to recall that since Venus Express is three-axis stabilized, ELS does not have $4\pi$ coverage. This problem is further exacerbated by the encroachment on the field of view of ELS by solar arrays and thrusters. Therefore, we have been forced to assume an
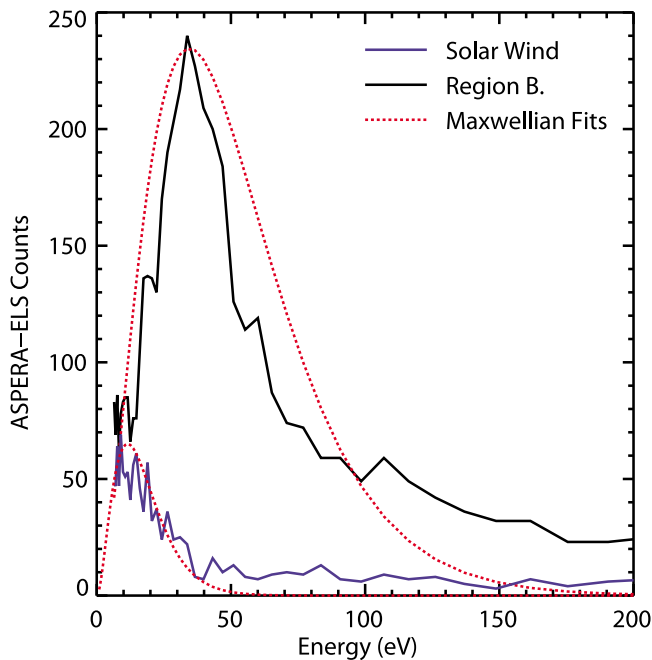
**Figure 5.** Contrasting the electron distributions observed in the solar wind at 03:48:33 UT with that of region B at 03:49:14 UT.

isotropic distribution, and thus the temperatures calculated here should be regarded as pseudomoments.

[29] Figure 5 contrasts the electron energy distribution in region B at 03:49:14 UT with that of the solar wind at 03:48:33 UT (the first time bin of Figure 3). We have hand-fitted Maxwellian distributions to both (red dashed lines). The full width at half maximum (FWHM) (temperature) of the distribution in region B is ∼58 eV, or ∼5 × $10^5$ K, where the FWHM of the solar wind fit is ∼20 eV, or ∼2 × $10^5$ K (compare $T_{e^-} = 1.4 \times 10^5$ K at Earth [*Kivelson and Russell*, 1995]). This is consistent with our interpretation of B as a region of heated plasma that has been compressed by the expanding HFA.

#### 4.2.4. Ion Spectrometer

[30] Figures 3f and 4e show data from the ASPERA ion mass analyzer (IMA). Figure 3d shows the deflection angle (look direction) of IMA for the given time bin. The solar wind ion population (most easily seen in Figure 4f) appears regularly between deflection angles of −5° to 22.5°, centered on a deflection angle of ∼5° and an energy of ∼2000 eV.

[31] A new population of ions appears during the HFA, centered at ∼1000 eV, in the two time bins between ∼03:48:42 and ∼03:49:30 UT. Since these time bins correspond to approximately −30° to −10° electrostatic deflection angles, these ions are coming from a different direction (as well as a lower energy) than from the solar wind. This population is not observed at any other time in the solar wind on this day, and we assert this to be qualitatively consistent with that of a deflection in plasma flow associated with an HFA. However, given the 192 s temporal resolution of IMA, it is not possible to plot distributions and positively confirm this.

### 4.3. Further Analysis

#### 4.3.1. Motional Electric Fields

[32] As noted in section 3, an important condition for HFA formation is thought to be that the motional electric field must point toward the discontinuity on at least one side (as in Figure 2) [*Schwartz et al.*, 2000]. Thus we have calculated the approximate motional electric field vector before $\bar{\mathbf{E}}_{pre}$ and after before $\bar{\mathbf{E}}_{post}$ according to

$$\bar{\mathbf{E}}_{pre} = -\hat{\mathbf{v}}_{sw} \times \bar{\mathbf{B}}_{pre} \qquad (2)$$

$$\bar{\mathbf{E}}_{post} = -\hat{\mathbf{v}}_{sw} \times \bar{\mathbf{B}}_{post} \qquad (3)$$

where we have assumed an antisunward solar wind velocity vector:

$$\hat{\mathbf{v}}_{sw} = (-1, 0, 0)$$

The resulting motional electric field vectors are plotted in Figure 3a as light blue arrows. Note that the length of the arrows are arbitrary, and all we are concerned with is their direction. It can be seen that for the Venusian HFA, both $\bar{\mathbf{E}}_{pre}$ and $\bar{\mathbf{E}}_{post}$ point toward the discontinuity, making this a textbook example of an HFA.

#### 4.3.2. Speed of Discontinuity

[33] Another condition believed to be required for HFA formation is that the point at which the discontinuity intersects the bow shock must move along the bow shock at a sufficiently slow speed enabling the particles reflected by the bow shock to have an effect on the discontinuity. According to *Schwartz et al.* [2000], to fulfill this condition, the ratio of the transit velocity of the discontinuity ($V_{tr}$) to the gyrovelocity of the reflected ion ($V_g$) must be less than 1, as in

$$\left| \frac{V_{tr}}{V_g} \right| = \frac{\cos \theta_{cs:sw}}{2 \cos \theta_{bs:sw} \sin \theta_{Bn} \sin \theta_{cs:bs}} \qquad (4)$$

(For a full description of equation (4), see *Schwartz et al.* [2000].) For the average shock angle before and after (region A, and solar wind region after, Figure 3), equation (4) yields a ratio of ∼0.6, and ∼0.9 which are in agreement with HFAs observed throughout the solar system. Again, we have assumed that this discontinuity is tangential.

### 5. Summary and Discussion

[34] In this paper we have presented the results of a case study of an HFA that struck the Venus Express on 22 March 2008 while in the solar wind upstream of the Venusian bow shock. The event is consistent with the following known properties of HFAs:

[35] 1. The event was centered on a magnetic discontinuity in the solar wind, (which we assume to be tangential) oriented quasi-parallel to the Sun-Venus line.

[36] 2. The velocity of the current sheet across the bow shock was calculated to be beneath the threshold thought to be required for HFA formation.

[37] 3. The motional electric fields were calculated to point toward the discontinuity, which is consistent with our understanding of HFA formation.

[38] 4. The magnetic field strength in the core of the event was very low, consistent with all known HFA observations.

[39] 5.The core of the event was bounded by compressed regions with increased electron flux and pseudotemperatures higher than that of the solar wind.

[40] 6. Ions were observed at a different energy, and from a different direction from the solar wind, consistent with a deflection in plasma flow.

[41] We therefore assert that this event is a Venusian hot flow anomaly, given that both field and particle measurements are consistent with our current understandings of HFAs. Now that it is has been shown that HFAs occur at Venus, we will briefly speculate on what effect they will have on the planet Venus. While it is impossible for us to make a direct observation without data from multiple spacecraft, we can speculate given what we know about how HFAs affect the magnetosphere of Earth, and the properties of the Venusian bow shock and ionopause [*Russell and Vaisberg*, 1983]. With no magnetic field, the bow shock of Venus is formed by the deflection of the solar wind flow by its ionosphere. The position of the bow shock and ionopause are dependent on the balance between internal pressure and the total pressure exerted by the solar wind. As such, the locations of these boundaries are highly variable [*Brace et al.*, 1980; *Russell et al.*, 1988; *Martinecz et al.*, 2008; *Brace and Kliore*, 1991]. However, we expect from previous numerical simulations that the HFA will expand sunward from the bow shock, deflecting solar wind ram pressure, and thus driving large sunward motions in the position of the bow shock [*Sibeck et al.*, 1999; *Jacobsen et al.*, 2009].

[42] For a first-order approximation as to how far the location of the Venusian ionopause ($R_i$) might shift from its nominal radial distance ($R_r \sim 250$ km at solar minimum), we have assumed a simple static Newtonian pressure balance between the total pressure inside the HFA ($\Sigma P_i$) and the total pressure outside in the solar wind ($\Sigma P_r$):

$$(R_i - R_r) = -H \ln\left(\frac{\Sigma P_i}{\Sigma P_r}\right) \qquad (5)$$

where $H$ is the scale height of the ionosphere. This simplistic model suggests that a significant decrease in solar wind pressure from an HFA increases the height of the ionopause by $\sim 210$ km (or almost doubling in height). We therefore speculate that HFAs have the potential to drive significant motions in the position of the Venusian bow shock and ionopause, and may possibly cause a disruption of orderly ionosheath flow. However, this remains an open question for further study and simulation.

[43] Our observation of hot flow anomalies at Venus, as first proposed by *Slavin et al.* [2009], confirms that it is credible that the magnetic signatures observed by MESSENGER were caused by HFAs. This also supports *Øieroset et al.* [2001], who suggested that HFAs can form in the foreshocks of unmagnetized planets. Thus, given that HFAs have been observed at Earth, Mars (probably), Saturn, and now Venus, it seems likely that they are indeed a ubiquitous phenomenon.

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