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# The response of the Venusian plasma environment to the passage of an ICME: hybrid simulation results and Venus Express observations

A. P. Dimmock<sup>1,2</sup>, M. Alho<sup>1</sup>, E. Kallio<sup>1</sup>, S. A. Pope<sup>3</sup>, T. L. Zhang<sup>4,5</sup>, E. Kilpua<sup>6</sup>, T. I. Pulkkinen<sup>1</sup>, Y. Futaana<sup>7</sup>, A. J. Coates<sup>8</sup>

<sup>1</sup>Department of Electronics and Nanoengineering, School of Electrical Engineering, Aalto University, Espoo, Finland

<sup>2</sup>Swedish Institute of Space Physics, Uppsala, Sweden

<sup>3</sup>Department of Automatic Control and Systems Engineering, University of Sheffield, UK

<sup>4</sup>Harbin Institute of Technology, Shenzhen, China

<sup>5</sup>Space Research Institute, Austrian Academy of Sciences, Graz, Austria

<sup>6</sup>Department of Physics, University of Helsinki, Finland

<sup>7</sup>Swedish Institute of Space Physics, Kiruna, Sweden

<sup>8</sup>Mullard Space Science Laboratory, University College London, London, UK

## Key Points:

- Response of Venus magnetosphere to an ICME has been studied by data analysis and hybrid model simulations
- Atypically large magnetic barrier (>250 nT), and magnetization of the ionosphere were observed
- Simulation resulted in a relatively nominal magnetic field draping pattern and about 30% increase of O<sup>+</sup> escape in the ICME run

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Corresponding author: Andrew P. Dimmock, [andrew.dimmock@irfu.se](mailto:andrew.dimmock@irfu.se)

## Abstract

Owing to the heritage of previous missions such as the Pioneer Venus Orbiter and Venus Express (VEX), the typical global plasma environment of Venus is relatively well understood. On the other hand, this is not true for more extreme driving conditions such as during passages of Interplanetary Coronal Mass Ejections (ICMEs). Some of the outstanding questions are how do ICMEs, either the ejecta or sheath portions, impact: 1) the Venusian magnetic topology, and 2) escape rates of planetary ions? One of the main issues encountered when addressing these problems is the difficulty of inferring global dynamics from single spacecraft orbits; this is where the benefits of simulations become apparent. In the present study, we present a detailed case study of an ICME interaction with Venus on 05 November 2011 in which the magnetic barrier reached over 250 nT. We use both VEX observations and hybrid simulation runs to study the impact on the field draping pattern and the escape rates of planetary  $O^+$  ions. The simulation showed that the magnetic field line draping pattern around Venus during the ICME is similar to that during typical solar wind conditions and that  $O^+$  ion escape rates are increased by approximately 30% due to the ICME. Moreover, the atypically large magnetic barrier appears to manifest from a number of factors such as the flux pile up, day-side compression, and the driving time from the ICME ejecta.

## 1 Introduction

Venus lacks any significant intrinsic magnetic field [Phillips and Russell, 1987]. For that reason, the Venus-solar-wind (SW) interaction generates an induced magnetosphere (IM) from the interaction between the highly conducting ionosphere and the incoming SW flow. Nevertheless, and remarkably so, the IM contains many similar boundaries and regions to those observed at intrinsic magnetospheres such as the case at Earth.

The global plasma environment of Venus and its magnetic topology during typical solar wind conditions are relatively well understood. Like Earth, a bow shock forms upstream (but stands off only around 1.5 Venus radii,  $R_V$ ), which is followed by a magnetosheath region downstream housing the shocked solar wind plasma. Forming inside the day-side magnetosheath is the magnetic barrier, which can be identified by the dominance of the magnetic pressure above all other pressure contributions (e.g. thermal and dynamic) [Russell *et al.*, 1979]. It is the magnetic barrier, as opposed to an intrinsic planetary magnetic field, that acts as an obstacle to the incoming solar wind flow [Zhang *et al.*, 1991]. The magnetic barrier ends where the magnetic pressure forms an equilibrium with the upstream solar wind dynamic pressure, and a magnetopause layer forms at the outer edge [Zhang *et al.*, 2007]. The Venus IM lies behind the magnetopause and extends to the ionopause, marking the boundary to the Venus ionosphere [Zhang *et al.*, 2008a]. In general, the day-side IM is referred to as the magnetic barrier, whereas the night-side is called the magnetotail. In the present paper, we refer to the IM as the region between the magnetopause and ionopause.

Another crucial aspect of the Venus-SW interaction is the acceleration, pick-up, and escape of planetary ions such as  $O^+$ . Heavy ion escape was reported by Mihalov and Barnes [1982], which were inferred from Pioneer Venus Orbiter (PVO) data. Although the identification of  $O^+$  from PVO data was achieved indirectly, it was proposed that the distribution of  $O^+$  is dictated by the SW convective electric field. This work has been furthered by VEX observations [Barabash *et al.*, 2007a] confirming that the convective electric field is the controlling parameter, and  $O^+$  escape occurs primarily in the plasma sheet — although pick-up can also occur in the magnetosheath. Nevertheless, it is crucial to obtain true ion escape rates to understand the dryness and oxidation of the Venus atmosphere, as well as the time history of water on Venus. However, understanding the global effects on Venus' plasma environment and ion escape during more extreme SW conditions is still an open area of study. An example of such events is ICMEs which con-

tain, amongst other features, atypically high upstream dynamic pressures and enhanced solar wind convective electric fields. Another motivation for this is that since ICMEs were speculated to be stronger and more frequent during more active solar periods [Wood *et al.*, 2005], these events may have had a significant impact on Venus' atmosphere and water.

ICMEs are separated into two distinct regions. By this, we refer to the sheath and ejecta regions since their formation as well as field and plasma properties are clearly separate (e.g. Kilpua *et al.* [2013]). ICME sheath regions are easily identified by their compressed and turbulent properties since they often contain high dynamic and thermal pressures, and their magnetic field directions have large amplitude and irregular fluctuations. The most turbulent parts of the sheath are downstream from a leading shock and upstream of the ejecta leading edge. In contrast, the ejecta exhibits a magnetic field profile which is smooth and slowly varying. They have typically much lower dynamic and thermal pressure than the preceding sheath. Here, we focus on the former, when Venus' IM was driven by an ICME sheath for over three hours. Such intervals can have dramatic impacts on the Venus environment due to the high upstream dynamic pressures [Russell, 1991; Edberg *et al.*, 2011], and thermalized particles.

Russell and Zhang [1992] and Zhang *et al.* [2008b] observed extremely distant bow shock crossings during Venus ICME encounters. The large upstream magnetic field strengths intrinsic to ICMEs can result in magnetosonic Mach numbers approaching unity, if the flow speed remains sufficiently low. As a result, atypically distant bow shock crossings have been observed. For example, Zhang *et al.* [2008b] reported a case where the Venus bow shock was crossed at 12  $R_V$ ; scaled to the Earth's magnetosphere, this equates to 180  $R_E$ . However, it should be noted that these have been observed during the ICME ejecta when the dynamic pressure can be very low. The shocks observed by Zhang *et al.* [2008b] and studied in detail by [Balikhin *et al.*, 2008] were a new type of shock, driven by pure kinematic relaxation.

Recently, a statistical study on the impact of ICMEs on the position of the Venusian bow shock and magnetic barrier was performed by Vech *et al.* [2015]. The authors reported that the upper and lower boundaries of the magnetic barrier were unaffected by the ICMEs. They also concluded that atypically large magnetic barrier crossings were the result of piled up magnetic field and not a manifestation of compression induced by a change in altitude of the magnetic barrier. The position of the day-side ionosphere was relatively constant, whereas the night-side ionospheric position decreased; they suggested that this is consistent with enhanced ion loss from large dynamic pressures.

What is also noteworthy, is that enhanced convective ( $\mathbf{E} = -\mathbf{U}_e \times \mathbf{B}$ ) electric fields (where  $\mathbf{U}_e$  is the bulk speed of electrons and  $\mathbf{B}$  is the magnetic field) during ICME intervals can accelerate and "pick-up" ions leading to their escape [Luhmann *et al.*, 2008]. In fact, the interaction between Venus and the SW is one of the only mechanisms in which heavy atmospheric elements can reach the required escape speeds [Luhmann *et al.*, 2008] of  $\sim 11$  km/s [Luhmann and Kozyra, 1991]. We should also stress that speeds must be outwardly directed (i.e. not to return to the exobase) for ion escape to be realized. This latter point demonstrates one of the pitfalls of making global interpretations from limited in-situ data. It is also important to remember that this effect can also be increased by the reduction of the ionopause altitude, thus exposing a larger area of the upper atmosphere to the solar wind [Luhmann and Cravens, 1991].

The escape of  $\text{O}^+$  was investigated by Luhmann *et al.* [2006] and Luhmann *et al.* [2007] using PVO observations. In their data, they reported that  $\text{O}^+$  fluxes were enhanced by  $\sim 100\times$  following large upstream dynamic pressure events such as ICMEs. However, the global interpretations from this study were limited by orbital coverage and short-lived extremes.

122 *Luhmann et al.* [2008] continued their work on  $O^+$  escape during ICMEs in a syn-  
 123 ergetic study using VEX measurements and MHD test particle simulations. The authors  
 124 reiterated the point that due to the dynamic nature of the spatial distribution of escaping  
 125 fluxes, the interpretation reached from in-situ measurements can be subjective based on  
 126 when and where they are sampled — motivating the use of a modelling element in their  
 127 study. The rotation of the planetary wake induced by Interplanetary Magnetic Field (IMF)  
 128 rotations can also add to this difficulty. One of the main results from this study was that  
 129 for certain IMF clock angles, the model suggested that no pick-up ions were present along  
 130 the spacecraft trajectory even though the global pick-up ion population in the model and  
 131 data were identical. The authors concluded that they were only able to conclusively report  
 132 enhanced escape of  $O^+$  in one case.

133 *Jarvinen et al.* [2009] performed a comparative study between VEX observations  
 134 and hybrid simulation runs. By comparing model and observed data, they could clearly  
 135 and accurately identify numerous regions (bow shocks, magnetic barrier, central tail cur-  
 136 rent sheet, magnetic tail lobes, magnetosheath and the planetary wake), indicating that the  
 137 model achieved consistent results with the data. The escape rates of  $O^+$  were also com-  
 138 puted in this study, and the authors reported that the best model-data fit was achieved  
 139 when  $O^+$  escape rates were between  $3 \times 10^{24} \text{ s}^{-1}$  -  $1.5 \times 10^{25} \text{ s}^{-1}$ . We should also mention  
 140 that their runs were computed ion escape for nominal solar wind conditions. These rates  
 141 are consistent with previously reported values between  $10^{24}$  -  $10^{26} \text{ s}^{-1}$  [*Moore et al.*, 1991;  
 142 *Barabash et al.*, 2007a].

143 In the present paper, we investigate the impact on the Venus plasma environment  
 144 during the passage of a ICME on 5 November 2011 using both observations and kinetic  
 145 hybrid model results. For the model runs and model-data comparisons, we focus explicitly  
 146 on the effect from conditions in the sheath region and not the ejecta. On this day, VEX  
 147 crossed the Venus bow shock after being driven by the ICME sheath region for over three  
 148 hours. The motivation for this study is the 250 nT magnetic barrier which to our knowl-  
 149 edge is the largest ever observed; it is the direct result of the ICME passage since typical  
 150 barrier strengths are 30-40 nT. We also investigate the factors which lead to such a re-  
 151 markable magnetic field strength. The timeliness of the orbital coverage with respect to  
 152 the event occurrence also present a rare opportunity to study the effects from the ICME  
 153 sheath component. We utilize both VEX observations and hybrid simulation results to  
 154 investigate the global response, which is not possible from the observations alone. High  
 155 resolution data is also examined to analyze the waves and turbulence present at the bow  
 156 shock and in the magnetosheath. In addition, from the simulations, we determine the  $O^+$   
 157 escape rate and compare this value to that calculated during ambient conditions and exist-  
 158 ing values found in the literature.

## 159 2 Experimental data and model description

### 160 2.1 Venus Express data

161 The present study utilizes observations made by the VEX [*Svedhem et al.*, 2007]  
 162 spacecraft between 4-6 November 2011 in which a ICME passed by the planet. The mag-  
 163 netic field measurements were recorded by the Venus EXpress MAGnetometer [*Zhang*  
 164 *et al.*, 2006] (VEX MAG) at a resolution of 1Hz and 32Hz. Since no magnetic cleanliness  
 165 program was implemented prior to launch, the VEX MAG instrument measures a super-  
 166 position of ambient and spacecraft generated magnetic fields. An extensive data clean-  
 167 ing program [*Pope et al.*, 2011] was implemented to produce a “cleaned” dataset com-  
 168 prised only of natural fields which is used here. A magnetic offset correction was also  
 169 required [*Leinweber et al.*, 2008] prior to a transformation from the VEX spacecraft ori-  
 170 entated frame, to the Venus Solar Orbital (VSO) co-ordinate system. Comparable to the  
 171 Geocentric Solar Ecliptic (GSE) frame, the VSO system has an x-axis orientated towards  
 172 the Sun, z-axis positive north and perpendicular to the orbital plane, and a y-axis complet-

173 ing the orthogonal set. In addition to VEX MAG data, we also employ plasma measure-  
 174 ments from the Analyzer of Space Plasma and Energetic Atoms (ASPERA-4) instrument  
 175 [Barabash *et al.*, 2007b] for the calculation of derived plasma properties and to obtain ini-  
 176 tial conditions for the simulation runs.

## 177 2.2 Hybrid model description

178 The adopted model has been continuously developed for over 15 years to study the  
 179 response of weakly and non-magnetized bodies to SW plasma properties. The model has  
 180 been applied to study the plasma environments of Mercury [Kallio and Janhunen, 2003],  
 181 Venus [Kallio *et al.*, 2008], the Moon [Kallio, 2005], and Mars [Kallio *et al.*, 2006a]. It  
 182 is a quasi-neutral hybrid Particle-In-Cell (PIC) model, and therefore ions are treated as  
 183 particles, moving in self-consistently calculated electromagnetic fields. Electrons act as a  
 184 charge-neutralizing massless fluid, i.e.:

$$185 \sum_i q_i n_i + q_e n_e = 0 \quad (1)$$

186 where  $(q_e, n_e)$  and  $(q_i, n_i)$  are the charge and number density of electrons and ions, respec-  
 187 tively. The ions in the model move under the Lorentz force  $\mathbf{F}_E = q(\mathbf{E} + \mathbf{U}_e \times \mathbf{B})$  where the  
 188 magnetic field  $\mathbf{B}$  is propagated in time from the electric field using Faraday's law,

$$189 \frac{d\mathbf{B}}{dt} = -\nabla \times \mathbf{E}. \quad (2)$$

190 The electric field is derived from the electron fluid momentum equation:

$$191 \mathbf{E} = -\mathbf{U}_e \times \mathbf{B} + \eta \mathbf{J} + \frac{\nabla p_e}{q_e n_e}. \quad (3)$$

192 Here,  $\mathbf{U}_e$  is the electron bulk velocity,  $\eta$  the electrical resistivity and  $p_e$  the electron ther-  
 193 mal pressure at constant temperature  $T_e$  ( $p_e = n_e k_B T_e$ ). Note, the electric current is de-  
 194 rived from Ampère's law in which the displacement current has been neglected (i.e. no  
 195 electromagnetic radiation is included). The magnetic field is then advanced forward in  
 196 time with a leapfrog algorithm by using equation 2 while particles are accelerated by the  
 197 Lorentz force. Note that divergence-free condition on the magnetic field is automatically  
 198 ensured by a Yee lattice grid structure where the magnetic field is assigned to cell faces.  
 199 Because of the hybrid approach, finite ion gyro-motion effects and Hall effects arise natu-  
 200 rally. Grid refinement techniques can be used to resolve specific area of the object's envi-  
 201 ronment with a higher precision [see Kallio and Janhunen, 2003, for more thorough tech-  
 202 nical details], although no refinements were employed in this study. We refer the reader to  
 203 Jarvinen *et al.* [2013] for a complete description of the implementation of the model for  
 204 the Venusian plasma environment. With the exception of the solar wind parameters, the  
 205 model setup is identical to the one in Jarvinen *et al.* [2013].

206 The simulation contains two sources of both planetary  $\text{O}^+$  and  $\text{H}^+$  ions: (i) photo-  
 207 ionization of exospheric neutrals as an extended source and (ii) emission of ionospheric  
 208 ions through the model exobase. The planetary ion production model is identical to the  
 209 one used by Kallio *et al.* [2006b], and later by Jarvinen *et al.* [2013]. Namely, the exo-  
 210 spheric cold  $\text{H}^+$  and hot  $\text{O}^+$  sources are separately modeled using the Chamberlain exo-  
 211 sphere model with a solar zenith (SZA) dependency, the hot  $\text{H}^+$  corona by an exponential  
 212 function of the form  $n(r) = e^{a_1 r + a_2 + a_3/r}$ , with the  $a_i$  having a SZ angle dependency (see  
 213 Kallio *et al.* [2006b] for details), and the cold  $\text{O}^+$  as emission of ions from the exobase.  
 214 These photon processes were the only sources of planetary ions employed.

215 The simulation does not include a self-consistent ionosphere, and therefore,  $\text{O}^+$  ions  
 216 originating from the ionosphere are considered by emitting  $\text{O}^+$  ions through the model  
 217 exobase (see Jarvinen *et al.* [2013] for details). The  $\text{O}^+$  emission from the model exobase  
 218 was  $1.0 \times 10^{25}$  1/s and the  $\text{O}^+$  photo-ionization rate was  $4.09 \times 10^{24}$  1/s, similar to our pre-  
 219 vious study (Jarvinen *et al.* [2013]). In each analyzed run, the total  $\text{O}^+$  ion production

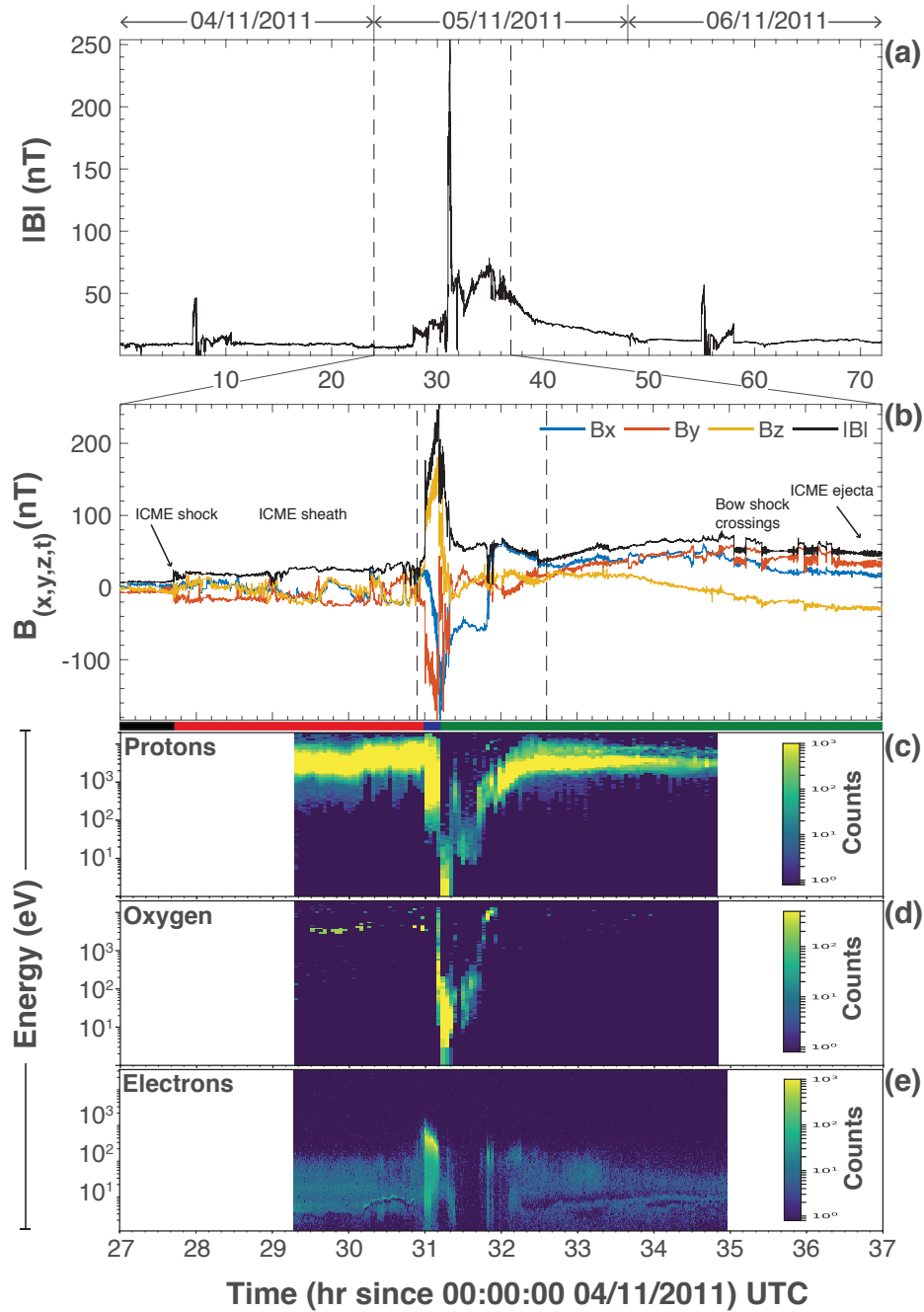
rate (exobase emission + photo-ionization) was kept constant at  $1.4090 \times 10^{25}$  1/s. Solar wind and planetary ions which hit the inner obstacle of the model (which represents the exobase) are removed from the simulation. From a physical point of view, this mimics the absorption of ions into the neutral atmosphere. It should be noted that in reality,  $O^+$  ions are formed also by electron impact ionization and charge exchange, and not only by photo-ionization. However, in the simulation, only photo-ionization was used in order to compare the previous runs by *Jarvinen et al.* [2013] and the new runs analyzed in this paper. The reason for this, is so that all simulations contain identical ion production, and consequently, that all differences between analyzed simulations were attributed purely to different solar wind plasma and field conditions. Finally, when the morphology of the magnetic field is analyzed, it is important to note that the model exobase is the inner obstacle in the simulation, below which the electrical resistivity is set to zero. Therefore, in the simulation, Venus is a superconducting ball inside which magnetic field cannot diffuse. A physical implication from this is that magnetic field lines may “slip” fast around the object. This treatment of the ionosphere may result in an underestimation of the total magnetic field, and impact the morphology of the magnetotail and draping pattern.

### 3 Venus Express observations

Presented in Figures 1 and 2 are observations by the VEX magnetometer and ASPERA-4 instruments over multiple time intervals surrounding the passage of the ICME. At around 03:40 UT on 05 November 2011, an ICME shock was detected. This was identified from the leading shock edge clearly visible from the sharp increase in the magnetic field gradient followed by an overall increase in the magnetic field strength downstream, as shown in panel(a). The enhanced field occurred in concert with elevated turbulence and large field rotations which are indicative of an ICME sheath region [*Kilpua et al.*, 2013]. Several hours later and clearly shown in panel (b), VEX encountered the planetary bow shock at 07:00 UT. This is evident from the dramatic increase of the magnetic field gradient typically associated with a quasi-perpendicular shock front. The actual shock geometry was estimated to be  $\theta_{bn} = 58.8^\circ$  by computing the angle between the shock surface normal,  $\hat{n} = [0.99, 0.07, 0.12]$ , and the average upstream magnetic field,  $\mathbf{B}_{up} = [19.06, -22.62, 26.17]$  nT. We estimated the bow shock compression ratio from  $B_{cr} = |\mathbf{B}_{up}|/|\mathbf{B}_{down}| = 3.44$ , where  $\mathbf{B}_{down}$  is the downstream magnetic field; this is compared to 2.9 on the previous day. Although the upstream flow speed is high, the Alfvén Mach number was moderate at  $M_A = 3.5$ , and therefore explains why no distant bow shock crossings [*Zhang et al.*, 2008b] occurred on this day. Since the behavior of the magnetic field profile between the ICME shock and the bow shock are consistent, it is our interpretation that VEX occupied the ICME sheath region until reaching the planetary bow shock.

Figures 1(c-e) and 2(b-d) show the particle data near Venus from the ASPERA-4 ions and electron sensors. The enhanced energy ( $\sim 3$  keV) of the solar wind protons upstream of the bow shock is consistent with the heated ICME sheath plasma. According to the ASPERA-4 particle instruments, the properties of the ICME sheath were:  $\mathbf{U}_i = [-820, -200, -300]$  km/s,  $n_i = 12$  cm $^{-3}$  and  $T_i = 60$  eV, which were averages computed immediately upstream of the bow shock. One can see in Figure 1c how the solar wind protons are heated and slowed down at the same time in the bow shock where the magnetic field is increased. The slowest protons can be identified near the planet where the magnetic field is at its maximum. The energy of protons starts to increase on the night-side when VEX moves farther from the planet back into the magnetosheath and the solar wind.

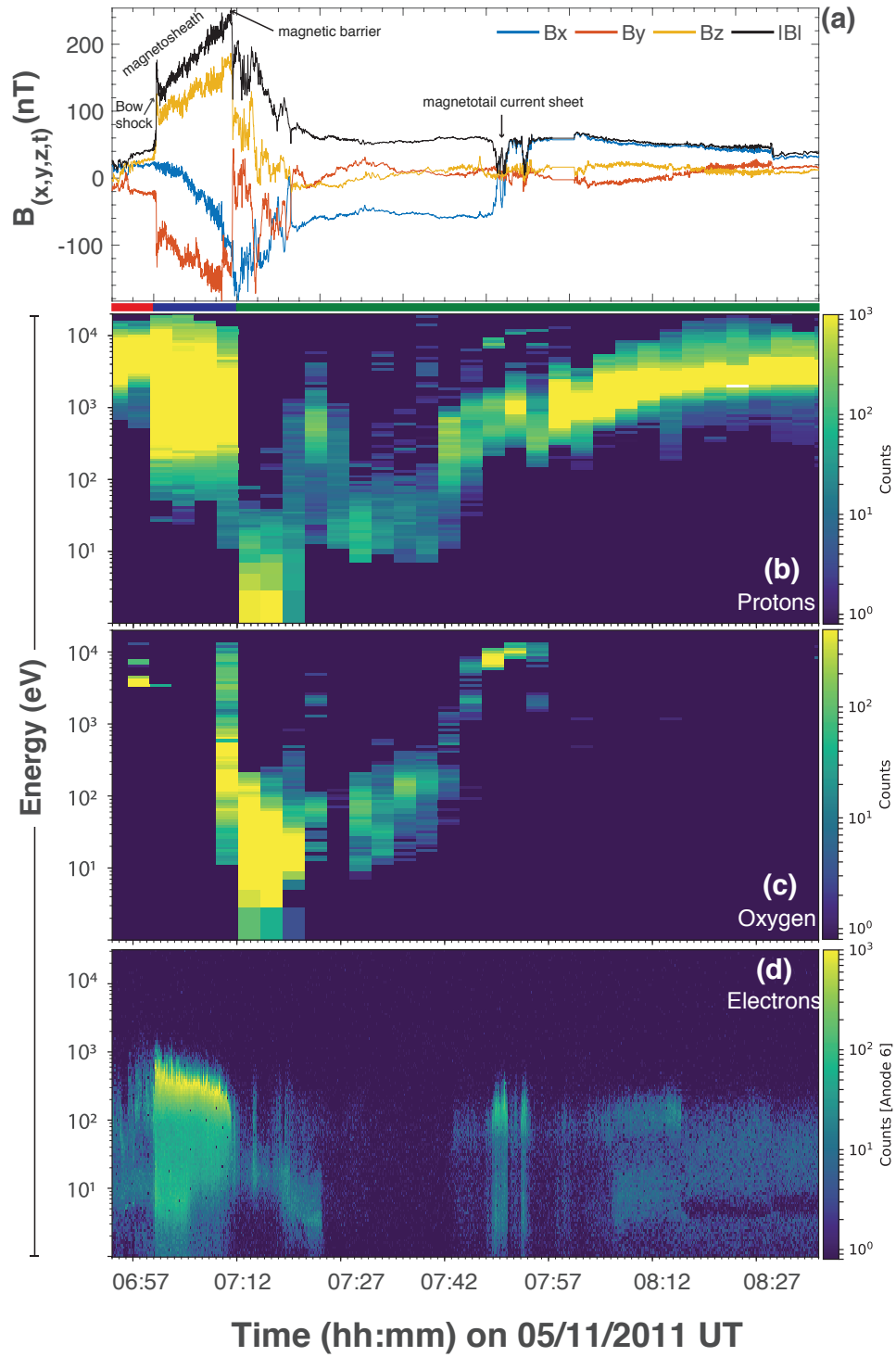
The electron data in panel (e) is also supportive of the identification of these regions and boundaries described above. The low energy electron population observed in the upstream region is indicative of a more positive spacecraft potential. This beam-like feature is sometimes seen in the electron data and is likely the result of differential charging [*Coates et al.*, 2008]. The higher energy electrons could be either the electron foreshock,



237 **Figure 1.** Overview plot of VEX MAG and ASPERA-4 data between 04 November 2011-06 November  
 238 2011. Panel (a) shows the VEX MAG data for the entire three-day interval. Panels (b-e) show the VEX MAG  
 239 and ASPERA-4 data for 03:00 - 13:00 05 November 2011 during the passage of the ICME. The colored bars  
 240 on the horizontal axes correspond to the regions of the orbital path plotted in Figure 3 later.

278 or associated with the dynamics of the ICME since a change in magnetic field orientation  
 279 occurs just prior to this at the beginning of the interval.

280 Interpretation of the oxygen ion data is complicated by the fact that protons can  
 281 “leak” from the Ion Mass Analyser (IMA) proton channel into the IMA heavy ion chan-



241 **Figure 2.** Same format as Figure 1(b-e) but for the shorter time interval of 06:54:00 - 8:36:00 05 November  
 242 2011.

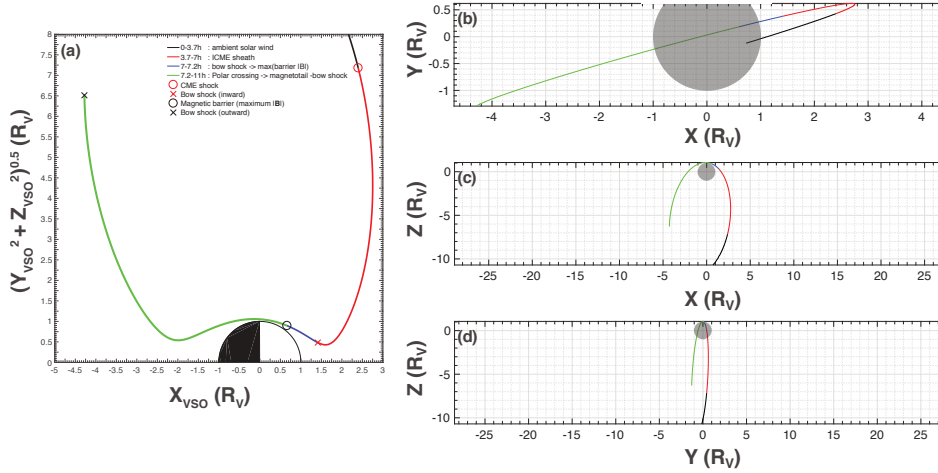
282 nel, making it difficult to ambiguously determine the relative contribution of oxygen ions  
 283 and protons in the IMA heavy ion data. For example, the high-count rate seen in the  
 284 heavy ion data in the solar wind at the same energy as where high solar wind protons

285 counts were observed suggest that these heavy ion counts are contaminated with solar  
 286 wind protons. A clear and high signal of planetary heavy ions can, instead, be seen in  
 287 Figure 2c at  $\sim 07:15$  near the pericenter. The energy of planetary ions increased when  
 288 VEX moved deeper into the Venusian tail and in the magnetosheath.

289 Figure 2 shows the magnetic field and particle data near the pericenter more clearly.  
 290 One can identify high energy  $O^+$  ions at  $\sim 07:25$  and again at  $\sim 07:50$ . At  $\sim 07:50$  and  $\sim$   
 291  $07:53$ , the magnetic field x component changes direction and there are heated electrons,  
 292 suggesting that VEX crossed the cross-tail current sheet and the plasma sheet. Although  
 293 these planetary ions can also be considered to have been “picked-up” by the solar wind,  
 294 their orbits more likely resemble a beam as opposed to the classical cycloid behavior of  
 295 pick-up  $O^+$  ions in the sense that their energy spectrum is rather narrow.

296 We should note that ICME sheath properties can change significantly when VEX  
 297 was near Venus. However, such changes cannot be determined once VEX crosses into  
 298 the downstream region. For example, in Figure 2, one can recognize a sudden appearance  
 299 of high energy protons and planetary ions at  $\sim 07:25$ . This would appear as if VEX had  
 300 entered for a moment back to the magnetosheath, which may suggest temporal changes  
 301 in the position of the magnetic barrier and the ionosphere below it. Moreover, there are  
 302 also decreases of the total magnetic field, and increase of the negative magnetic field x-  
 303 component at  $\sim 07:18$  and  $\sim 07:20$  — similar to the data later at  $\sim 07:50$  and  $\sim 07:53$ . This  
 304 may indicate that the IMF and, consecutively, the magnetic field draping pattern, have varied  
 305 during the flyby. Thus, any effects from the lack of an upstream monitor are excluded  
 306 from our analysis, which may manifest as differences between the model-data comparisons  
 307 we perform later.

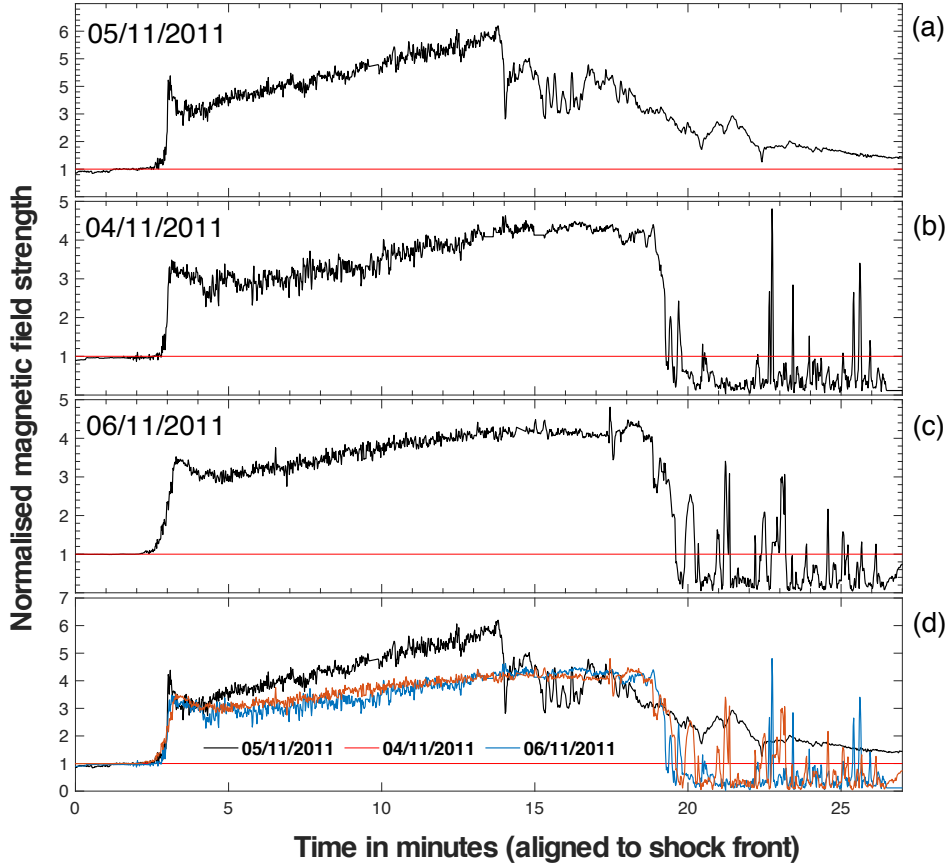
312 Figure 3 provides an overview of the spacecraft orbit on 05 November 2011 from  
 313 00:00:00 (solar wind) until leaving the Venus magnetotail into the ICME ejecta. The  
 314 ejecta is identified from the smooth field rotation [Burlaga *et al.*, 1981] which is in large  
 315 contrast to the ICME sheath. Interestingly, on closer inspection, the outbound bow shocks  
 316 from approximately 35 hours in Figure 1a are kinematic relaxation shocks [Balikhin *et al.*,  
 317 2008; Zhang *et al.*, 2008b]; this is noteworthy since such shocks are seldom observed and  
 318 although beyond the scope of the current study, the conditions leading to their occurrence  
 319 is worthy of further investigation. The orbital path is presented in a cylindrical co-ordinate  
 320 plane in panel (a) such that the two axes correspond to  $x$  and  $\sqrt{y^2 + z^2}$ . The  $xy$ ,  $xz$ , and  
 321  $yz$  are plotted in panels (b-d). Notable time intervals (in hours) have been labeled to mark  
 322 regions and boundaries of interest. These are: (0-3) solar wind, (3-7) ICME sheath, (7-  
 323 7.2) magnetosheath - magnetic barrier, and (7.2-11) magnetic barrier - magnetotail - out-  
 324 ward bow shocks. These regions have also been marked in Figure 1 panels (b & c) by  
 325 the matching colored horizontal bars. VEX is in a highly polar orbit but crosses the bow  
 326 shock on the equatorial nose, which is consistent with the estimate of the bow shock nor-  
 327 mal that points towards the Venus-Sun line. The spacecraft then moves toward the polar  
 328 region, but before this, the VEX MAG instrument measures an outer edge magnetic barrier  
 329 strength approximately 250 nT. To our knowledge, this is the largest magnetic barrier  
 330 strength recorded by VEX. For reference, according the panel (a) in Figure 1, this is over  
 331 four times the typical value ( $\sim 50$  nT) for similar orbital geometries, as demonstrated by  
 332 the data measured on 04 November 2011 and 06 November 2011. In general, the mag-  
 333 netic pressure at the magnetic barrier should balance the upstream dynamic pressure along  
 334 the barrier normal [Zhang *et al.*, 1991]. In the cases of ICME sheath driving, however,  
 335 there can be a significant thermal upstream pressure from the shocked solar wind plasma.  
 336 Therefore, it is likely that the simple (dynamic) pressure balance can be violated. In addi-  
 337 tion, the three-dimensional nature of the magnetic barrier region may prevent the applica-  
 338 tion of a simple one-dimensional pressure balance equation for the ICME interaction.



308 **Figure 3.** Orbit of VEX on 05 November 2011 in cylindrical co-ordinates  $\hat{x}$  and  $\sqrt{\hat{y}^2 + \hat{z}^2}$  (a),  $xy$ ,  $xz$ , and  
 309  $yz$  planes (b, c, d), respectively. The color of the line indicates specific intervals during the orbital period and  
 310 the markers show the crossing of important boundaries. The VEX MAG data for these regions are shown and  
 311 labeled in Figure 1.

### 3.1 Magnetic Barrier and Ionosphere

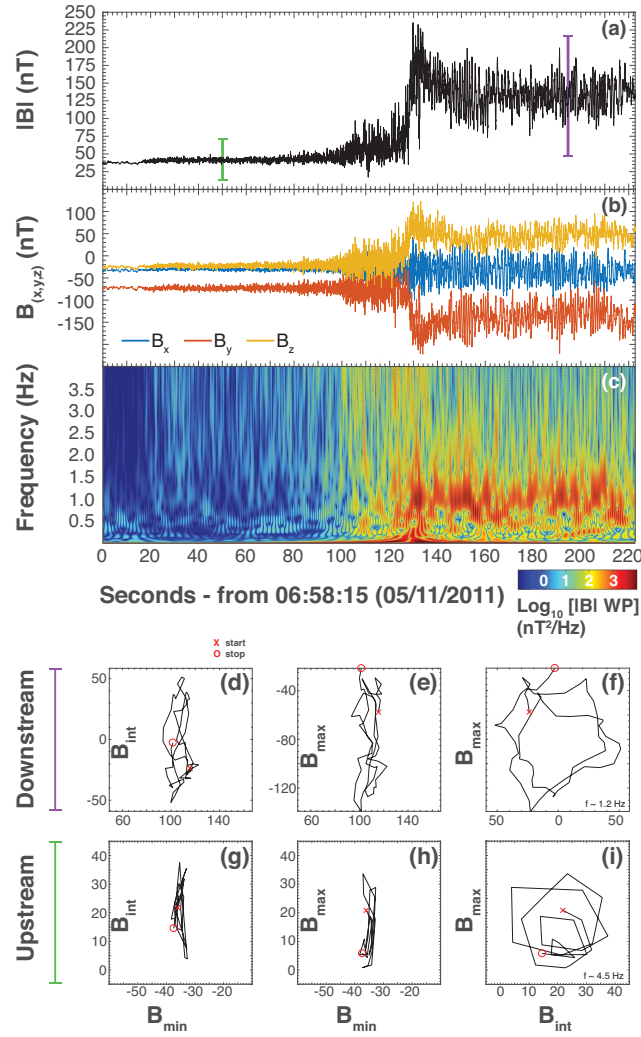
348 Figure 4 shows a plot of the magnetic field modulus for three different Venus pas-  
 349 sages. Panel (a) corresponds to 05 November 2011 which is presented in Figure 2. The  
 350 remaining intervals are on the surrounding days when the orbital track is similar. The  
 351 magnetic field measurements have been normalized by the field strength immediately up-  
 352 stream of the bow shock. There are several interesting observations to note from Figure  
 353 4. Firstly, the compression ratio ( $B_{up}/B_{down}$ ) of the bow shock is larger during the ICME  
 354 passage, resulting in a larger downstream magnetic field strength. However, this is not in  
 355 itself enough to explain such a large magnetic barrier. Secondly, visually comparing the  
 356 three panels clearly shows that the magnetosheath traversal is notably shorter in panel (a).  
 357 This could be indicative of an additional compression on the day-side and is also consist-  
 358 ent with the fact that the magnetic field gradient as VEX traverses the magnetosheath is  
 359 much greater. If we are to compute the relative increase of the magnetic field from down-  
 360 stream of the bow shock to the peak of the barrier strength, then the ICME ratio is ap-  
 361 proximately 1.9 compared to 1.4 and 1.3 on the pristine driven days. When VEX reaches  
 362 the magnetic barrier, it is almost six times greater than the upstream field strength com-  
 363 pared to approximately four in the other examples. This could also be an indication of  
 364 enhanced flux pile-up, contributing to the magnetic barrier strength. Finally, the magnetic  
 365 field profile following the magnetic barrier crossing is very different in panel (a), and does  
 366 not exhibit the similar sudden drops in magnetic field strength to less than the upstream  
 367 value in panels (b & c). It is worth noting that in panel (a) the magnetic field strength  
 368 remains above its upstream value (red line) even though the spacecraft has crossed signif-  
 369 icantly into the night-side. The bow shock distance was closer on 05 November 2011 by  
 370 around  $0.2 R_V$ , but the magnetic barrier location (based on maximum field strength and  
 371 subsequent drop) was relatively unchanged — hence the shorter magnetosheath traversal.  
 372 We direct the readers to the recent paper by *Vech et al.* [2015] for a comprehensive study  
 373 on the evolution of the boundary locations.



340 **Figure 4.** Selected intervals of VEX MAG data on 05 November 2011(a), 04 November 2011(b) and 06  
 341 November 2011(c). The top panel is during the ICME encounter and shows larger day-side compression due  
 342 to the much shorter traversal of the magnetosheath. The relative magnetic field strengths are significantly  
 343 enhanced during the ICME. The interval following the magnetic barrier in panel (a) is in stark contrast to  
 344 the other panels, suggesting the ICME driving influences the ionosphere, and the ionopause boundary. The  
 345 horizontal red line marks the value 1 for reference. Panel (d) shows each interval overlaid for comparison and  
 346 clearly demonstrates the differences in normalised strength and differing nature of the magnetic field after the  
 347 barrier crossing.

### 374 3.2 32Hz VEXMAG observations

384 The smaller scale features of this event should be investigated since they can provide  
 385 valuable insight into the presence of pick-up ions, energy conversion/dispersion, and  
 386 also provide evidence of how the local and global plasma conditions are regulated. For  
 387 that reason, presented in Figure 5 is an interval of high resolution (32Hz) measurements  
 388 made by the VEX MAG instrument over a 220 second interval starting from 06:58:15  
 389 UT on 05 November 2011. The data corresponds to a traversal by VEX from upstream  
 390 (ICME sheath) to downstream — the ICME sheath to the Venus magnetosheath. Plotted  
 391 in panel (a) is the magnetic field modulus whereas the x, y and z components are displayed  
 392 in panel (b) below. A wavelet spectrogram of  $|\mathbf{B}|$  is included in panel (c), showing  
 393 the spectral properties up to 4Hz. Panels (d-i) show hodograms of the downstream  
 394 and upstream waves over approximately 2 wave cycles. The purple and green vertical  
 395 lines in panel (a) mark the instance that these were computed. What is immediately ob-  
 396 vious from Figure 5c is the increase in amplitude of fluctuations above 1Hz from ap-



375 **Figure 5.** VEX MAG measurements recorded at 32Hz. The interval demonstrates the spacecraft crossing  
 376 from the upstream (ICME sheath) to the downstream Venus magnetosheath. The entire interval shown here  
 377 was during the time that the ICME sheath was passing Venus. Panel (a) shows  $|\mathbf{B}|$  whereas the x, y and z  
 378 components are plotted below in panel (b). A wavelet spectrogram of  $|\mathbf{B}|$  is plotted in panel (c) and the color  
 379 scale corresponds to the  $\text{Log}_{10}$  of the wavelet power. It is clearly shown from panel (c) that there are well  
 380 defined wave packets both upstream and downstream of the bow shock at multiple frequencies. Hodograms  
 381 from minimum variance analysis of the upstream and downstream wave packets are included in panels (d-i),  
 382 and suggest near circular polarization for both cases. In these panels, subscripts min, int and max correspond  
 383 to the magnetic field along the minimum, intermediate, and maximum variance directions.

397 proximately 20 seconds. The upstream region (20s-100s) shows higher frequency ( $>1$   
 398 Hz) waves which extend far into the upstream region. There are also waves housed in  
 399 the bow shock foot region which are of similar frequency, but higher amplitude. Down-  
 400 stream of the bow shock from 130s, there are large amplitude ( $B_{RMS}/B_0 \sim 0.2$ ) waves  
 401 which persist for approximately 80 seconds. The signature of these waves appeared to  
 402 be damped soon after this interval. The hodograms from both upstream and downstream  
 403 suggest the wave packets are almost circularly polarized ( $\lambda_{int}/\lambda_{max} \sim 1$ ) and (where  
 404  $\lambda$  are the eigenvalues of the co-variance matrix) propagate obliquely at an angle of  $34^\circ$

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**Table 1.** Input parameters to the kinetic hybrid simulations for the three runs used in this study.

Parameter	nominal	ICME $n_{12}$	ICME $n_{20}$
dx / km ( $R_V$ )	302.59 (0.05)	302.59 (0.05)	302.59 (0.05)
dt / s	0.02	0.01	0.01
domain extents / km ( $R_V$ )	$\pm 18155.4 (\pm 3)$	$\pm 18155.4 (\pm 3)$	$\pm 18155.4 (\pm 3)$
inner boundary (exobase) radius / km	6251.8	6251.8	6251.8
macroparticles per cell	30	30	30
Solar wind IMF,  IMF  / nT	[6,-5,0], 7.81	[20,-20,20], 34.64	[20,-20,20], 34.64
Solar wind bulk velocity / km/s	[-400, 0, 0]	[-800, -200, -300]	[-800, -200, -300]
Solar wind proton density / $\text{cm}^{-3}$	8	12	20
Solar wind proton temperature / K	116045	696270	696270
Isothermal electron temperature / K	10000	10000	10000

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(upstream) and  $35^\circ$  (downstream) with respect to the average background field direction. The frequency of the upstream (downstream) waves are approximately 4.5Hz (1.2 Hz) which compared to the local proton gyro-frequency of 0.6 Hz (1.95 Hz). There are a number of candidates for these waves such as whistler waves [Russell, 2007], ion cyclotron waves [Delva et al., 2008; Wei et al., 2011], and nonlinear magnetic structures [Walker et al., 2011]. It is our interpretation that the waves upstream are Doppler shifted whistler mode waves as similar dispersive wave-trains are commonly observed upstream of planetary bow shocks [Dimmock et al., 2013] with comparable characteristics. We also suggest that the downstream waves are also likely whistler waves transmitted from upstream. We also investigated the possibility that the downstream waves were ion cyclotron waves, however, although this analysis proved inconclusive as they appeared to propagate obliquely to the background field direction. Nevertheless, we have not eliminated this possibility since: 1) both wave-modes can exist here, 2) it is difficult to confirm a wave-mode with 1 spacecraft and 3) some properties (e.g. frequency) of the structures are consistent with multiple wave-modes.

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#### 4 Venus Express and hybrid simulation comparison

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For a global perspective, we utilize hybrid simulations for the ICME interval. For the ICME sheath input conditions, we made two runs: one with the measured density ( $n_{12}$ ) of  $12 \text{ cm}^{-3}$ , and another with a significantly increased upstream density of  $20 \text{ cm}^{-3}$  ( $n_{20}$ ). We also made an additional run for nominal upstream conditions to compare with the ICME runs. The list of model input parameters for the three runs can be found in Table 1. The reason for making these two runs was to determine the impact from the upstream density (and subsequent external pressure) on the model result. This is an important question since the density can be large and often underestimated during extreme upstream conditions. The primary goals for the model-data comparison and model data analysis were to: 1) determine if the model could approach the strength of the magnetic barrier with atypically larger upstream densities, 2) determine the impact on the  $\text{O}^+$  escape rates for different upstream densities, and 3) study the differences between the model and experimental magnetic topology during such extreme driving conditions. For comparative purposes, a run for nominal conditions was also generated ( $\mathbf{B} = [6.0, -5.0, 0.0]$  nT,  $n_i = 8 \text{ cm}^{-3}$ ,  $U = [-400, 0, 0]$  km/s). In this section, we compare the observations with the model solutions. As an error metric, we compare the field line draping in the model to the one measured by VEX. We exploit a feature of the model to attempt to optimize the angle between the model and the measurement, in effect, “mimicking” a variation in the upstream clock angle.

441 The simulation is set up with cylindrical symmetry in all parameters describing the  
 442 planet, except for IMF clock angle. Thus, the results of a single simulation can be trans-  
 443 formed by a rotation about the x axis to match a different IMF clock angle, when the solar  
 444 wind is flowing along the x-direction. Therefore, a single run can be used to analyze the  
 445 set of given upstream parameters, the IMF clock angle taking any value and all other pa-  
 446 rameters held constant. When applied to dynamic variations in the solar wind, we need  
 447 to assume, additionally, that changes in solar wind are slower than the response times of  
 448 the system, and that there are no hysteresis effects. Both assumptions may be violated in  
 449 reality, but we still regard the method as a useful approximation. This is utilized when  
 450 comparing the VEX observations with the hybrid model results, since any rotation about  
 451 the x-axis of the simulation domain can account for unknown clock angle variations.

452 For each VEX orbital point, we identify the corresponding hybrid model grid. We  
 453 then trace a circular path in the yz plane with radius  $|\mathbf{R}_{vex}|$  with an angular resolution of  
 454  $1^\circ$ . This is equivalent to rotating the hybrid model box at  $1^\circ$  increments, which adjusts the  
 455 model solution for changes in the IMF clock angle. From this point, we denote this angle  
 456 as  $\Theta$ , and  $\Delta\Theta$  is the angular displacement from the beginning of the circular path. At each  
 457 point on the circular path,  $\mathbf{B}_{hyb}$  is interpolated and a rotation about the axis of  $-\Delta\Theta$  is ap-  
 458 plied ( $\mathbf{B}_{hyb}^*$ ). From this point, subscripts of hyb refer to simulated parameters. The angle  
 459 between  $\mathbf{B}_{vex}$  and  $\mathbf{B}_{hyb}^*$  is measured and recorded ( $\theta_o$ ). This procedure is repeated for  
 460 each VEX orbital point which falls in the hybrid model simulation domain and points out-  
 461 side the simulation model limits are excluded. The optimal orbital point is selected based  
 462 on the minimum value of  $\theta_o$  at each location. Prior to this procedure,  $\mathbf{B}_{vex}$  is smoothed  
 463 by a 60-point moving average filter. The purpose of this is to decrease the impact from  
 464 small scale temporal and spatial magnetic field variations which are not included in the  
 465 hybrid model.

#### 466 4.1 Optimization for ICME day: 05 November 2011

480 Presented in Figure 6 is a comparison of  $\mathbf{B}_{vex}$  and  $\mathbf{B}_{hyb}^*$  for the data collected on  
 481 05 November 2011. Here we show data from the n<sub>20</sub> ICME run in which the upstream  
 482 density was  $20 \text{ cm}^{-3}$ . The simulated points were selected based on the minimization of  
 483  $\theta_o$ . Panels (a-c) show each component in which subscripts 1 and 2 (e.g.  $a_{1,2}$ ) correspond  
 484 to the actual values and those normalized by the root mean squared (RMS), respectively  
 485 — computed over the entire interval. Panel (d) corresponds to  $\Theta_r$ , and is the angle of  
 486 VEX, in the yz plane. Any changes in  $\Theta_r$  can be interpreted as variations in the IMF  
 487 clock angle. The units of the x-axis are given in both data-points and UT time according  
 488 to the VEX measurement. For reference, the bow shock is crossed at approximately 3400  
 489 data-points. The interval prior to the bow shock crossing is the ICME sheath region. The  
 490 optimization procedure is immediately obvious here since the simulated  $B_x$  remains al-  
 491 most constant (as the rotation is about the x-axis) while the other components track the  
 492 ICME field rotations relatively accurately. What is clear from Figure 6 panels (a1, b1,  
 493 c1) is that the simulation generally underestimates the magnitudes of  $\mathbf{B}_{vex}$ . Having said  
 494 that, the normalized components shown in panels (a2, b2, c2) suggest that the trend of the  
 495 magnetic field components are well reproduced in the simulated data if the magnitudes  
 496 of each component are appropriately scaled. Between data-points 5000-7000 (i.e. mostly  
 497 covering R3 and R4 which covers the periapsis and magnetotail until the cross-tail current  
 498 sheet), the measured and simulated profiles diverge, and this is particularly visible in the  
 499  $B_y$  and  $B_z$  components shown in panels (b & c). Note, we suspect at this point, the up-  
 500 stream driving has transitioned from ICME sheath-ejecta. It should also be stated that the  
 501 RMS normalization does not correct this, therefore the magnetic field orientations differ  
 502 in this region between the measured and simulated data. To quantify the error associated  
 503 with the optimization, we have plotted the probability distribution functions (PDFs) of  $\theta_o$   
 504 for five regions labeled R(1-5) in panel (e). These regions are marked by the color-bars at  
 505 the top of panels (a1, b1, & c1). The orbital location of each region is shown in panel (f).  
 506 In general, region 1 shows a multi-modal distribution of error, albeit this is to be expected

507 from the static model input conditions, compared to the dynamic and transient observa-  
 508 tions. R2, which corresponds to the bow shock crossing and up to the magnetic barrier,  
 509 shows a high degree of agreement, and the angle is typically between  $1^\circ$  and  $5^\circ$ . R3 cov-  
 510 ers the trajectory from the magnetic barrier and across the periapsis. Even though the er-  
 511 ror increases here,  $\Theta_o$  is typically less than  $15^\circ$ . Moving into the magnetotail (which is  
 512 R4), the error increases and is spread over  $80^\circ$ , indicative of a poor solution between the  
 513 observed and modeled field directions. The error appears to decrease for the latter part of  
 514 the orbit in R5, in which  $\Theta_o$  is around  $20^\circ$ .

#### 515 **4.2 Optimization for nominal day: 29/10/2011**

518 Presented in Figure 7 are the results from simulation-data optimization, except in  
 519 this case the procedure was performed during a period of nominal solar wind conditions.  
 520 The format of Figure 7 is the same as in Figure 6. Due to the absence of any clear solar  
 521 wind structures or significant IMF rotations, the optimization shows good performance in  
 522 the upstream region (R1) with errors approximately  $10^\circ$ . This is in contrast with the previ-  
 523 ous interval in which errors over the comparable region were around  $80^\circ$ . It is particularly  
 524 striking that the day-side errors are comparable between the ambient and extreme periods  
 525 (see Figure 6g and Figure 7g); this point will be discussed in more detail in the following  
 526 section. The largest differences between the two runs is in the night-side/magnetotail (R4  
 527 and R3). In the ICME case, no consistent model-data optimization was possible on the  
 528 night-side. During the nominal interval, the errors for R4 consistently converged to around  
 529  $20\text{-}30^\circ$ , and there were negligible errors beyond  $40^\circ$ .

## 530 **5 Hybrid simulation results: nominal vs ICME driving**

### 531 **5.1 Overview**

539 Shown in Figure 8 is a comparison between the  $n_{20}$ ,  $n_{12}$ , and the nominal runs.  
 540 Each case is a slice from the model result which is taken from the plane that lies perpen-  
 541 dicular to the upstream solar wind flow, and which contains the undisturbed IMF vectors –  
 542 the VSO orientation is displayed in the bottom left of each panel. The color in each panel  
 543 corresponds to the solar wind proton density, whereas the contour lines and color repre-  
 544 sent the magnetic field magnitude. The streamlines are also included and their color in-  
 545 dicates the speed. What is immediately obvious, is that there is a global increase of solar  
 546 wind proton density during the ICME for both the  $n_{12}$  and  $n_{20}$  runs. The magnetic field  
 547 strengths are also enhanced, particularly at the magnetic barrier for the ICME runs com-  
 548 pared to nominal conditions. It is also clear that by increasing the upstream number den-  
 549 sity, the magnetic barrier also increased. Although the general behavior of the model as a  
 550 function of the strength of the upstream driving conditions is consistent with the observa-  
 551 tions, the model continually underestimates the magnetic barrier recorded by VEX. Having  
 552 said that, there does not appear to be a significant impact on the magnetic field draping  
 553 pattern between the three model runs. In the next section we examine the field line drap-  
 554 ing properties in more detail.

### 555 **5.2 Field line draping**

561 Presented in Fig. 9 is the magnetic field draping during the nominal (left column)  
 562 and ICME (middle and right column) runs. The draping is presented in an aberrated frame  
 563 using the upstream solar wind vector in which the VSO direction is marked next to each  
 564 panel. Note that in the nominal case, the solar wind flow is approximately parallel to the  
 565 VSO x-axis, and therefore the VSO and aberrated-nominal frames are quite similar. On  
 566 the other hand, the aberrated-ICME differs to the VSO frame due to the rather oblique up-  
 567 stream flow direction — reflected by the rotated VSO axes. It is worth noting that data  
 568 which has been rotated (around x), corresponding to the magnetic field vector, also rep-

569 resent conditions where the direction of the transverse velocity component is also rotated  
 570 about the x-axis. Therefore, all rotated simulation cases correspond to cases which had  
 571 the same upstream  $U_x$  and the same magnitude of the total transverse solar wind veloci-  
 572 ty component  $\sqrt{(U_y^2 + U_z^2)}$  — but, the transverse components were rotated by the best  
 573 fit rotation angle about the x-axis. In principle, this causes uncertainty in the optimiza-  
 574 tion procedure since the actual flow orientation is unknown. In practice, the impact from  
 575 such effects could be estimated by making hundreds of runs for different directions of the  
 576 transverse velocity component and analyzing model-data discrepancies in detail. However,  
 577 since we focus on the differences between the magnetic topology, such extensive computa-  
 578 tions are beyond the scope of this study; but this assumption should be kept in mind.

579 In both cases, several key regions can easily be identified such as the bow shock,  
 580 magnetic barrier, and the magnetotail. Interestingly, in both cases, the magnetic field drap-  
 581 ing patterns are very similar. To put this into context with the model-data comparison,  
 582 this implies that the large differences between the simulated and observed magnetotail (see  
 583 Figure 6) are likely induced by variable upstream conditions which the model cannot ac-  
 584 count for.

585 From Figure 6 we can see that there is a large deviation between the observations  
 586 and the model magnetic field directions in R4. In the observations, the magnetic cloud  
 587 structure can clearly be seen superimposed on the VEX magnetotail, so it is a logical as-  
 588 sumption that the upstream driving has changed from the sheath to the ejecta components  
 589 of the ICME. It is not possible to identify the exact time interval at which the change in  
 590 the external driving occurred, however, since there is no notable sharp changes in the ob-  
 591 servations between the bow shock crossing and the magnetic barrier; it is our interpre-  
 592 tation that it occurred between R3-R4 (after the magnetic barrier) which corresponds to  
 593 an interval from 07:10 - 07:25 on 05 November 2011. The model-data divergence would  
 594 occur due to the fact that the ICME ejecta significantly alters the magnetic profile of the  
 595 magnetotail — which is not included, and cannot be accounted for by the model. Thus,  
 596 in the absence of any variations in the external driving conditions, the draping pattern is  
 597 similar for the nominal and static modeled ICME driving conditions.

612 It can be seen in Figure 2 that in the ICME case, the observed magnetic field direc-  
 613 tion fluctuates below the magnetic barrier in R3. This is also visible in the clock angle  
 614 optimization procedure in Figure 6d. Taking the optimized clock angles from the proce-  
 615 dure for times T2 and T3, we can compare the magnetic morphology of the simulations  
 616 against the observations, accounting for clock angle dynamics, as demonstrated in Fig-  
 617 ure 10. In R2, the correspondence is high with the optimized rotation at time T2, but R3  
 618 could be seen to be composed roughly of magnetic field perturbations corresponding to  
 619 rotations at T3 (when entering and leaving R3) and the rotation of the previous region at  
 620 time T2 (within R3). The differences between the two R3 magnetic field populations are  
 621 substantial if they are interpreted as clock angle rotations.

622 Using field rotation at time T3, the morphology corresponds to equator-like draping,  
 623 while with time T2, the draping corresponds better with the draping pattern close to the  
 624 nominal pole regions. Notably, the R3 is below the magnetic barrier and at low altitudes,  
 625 hinting to the possibility of remnant solar wind magnetic fields being observed. Indeed,  
 626 the rough correspondence between a population of observed magnetic fields and field ori-  
 627 entation corresponding to previously observed upstream conditions would be consistent  
 628 with this interpretation.

### 629 5.3 Planetary $O^+$ and escape

630 During the crossing of the magnetotail, the VEX ASPERA-4 instrument detected  
 631 heavy ions with energies of approximately 10 keV, as seen in Figure 2. These ions were  
 632 also reported by *Vech et al.* [2015] to be planetary pick-up ions, and we agree with this  
 633 conclusion. What is noteworthy, is that these energies are consistent with the required

645 **Table 2.** Simulated total O<sup>+</sup> escape rates (1/s) for the ICME interval, and during nominal conditions. In all  
 646 cases, the total O<sup>+</sup> production rate within the simulation box was fixed as  $1.4090 \times 10^{25} \text{ s}^{-1}$ . The O<sup>+</sup> impact  
 647 rate, i.e. the rate of O<sup>+</sup> ions absorbed at the model exobase, is shown for comparison. The rates are calculated  
 648 from a 50 second average, after the simulations had reached a quasi-stationary state.

Parameter	Nominal	ICME $n_{12}$	ICME $n_{20}$	% change $n_{12}$	% change $n_{20}$
Escape rate	$2.4809 \times 10^{24}$	$3.0886 \times 10^{24}$	$3.2385 \times 10^{24}$	+24.5	+30.5
Impact rate	$1.1063 \times 10^{25}$	$1.0601 \times 10^{25}$	$1.0547 \times 10^{25}$	-4.2	-5.03

634 quantity to achieve O<sup>+</sup> [Luhmann *et al.*, 2008] escape. Having said that, it is extremely  
 635 difficult to infer O<sup>+</sup> escape from such limited spatial coverage — especially since the  
 636 probe is not located in the mid-to-distant wake, where outward heavy ion trajectories are  
 637 more reliable evidence [Luhmann *et al.*, 2008]. For this reason, we utilize hybrid simula-  
 638 tion runs to obtain a more global perspective and convincing evidence of O<sup>+</sup> escape. In  
 639 order to test the sensitivity of the O<sup>+</sup> escape rate on the solar wind density, we made the  
 640 calculations for both the  $n_{12}$ , and the  $n_{20}$  runs.

649 Plotted in Figure 11 are the planetary O<sup>+</sup> streamlines for the ICME  $n_{20}$  (a) and  
 650 nominal (b) runs. The color of each streamline corresponds to the value of the model  
 651 omni-directional flux. In both plots, the streamlines are propagated from close to the exobase,  
 652 which is approximately 200 km. The arrows indicate the directions of the convective ( $-\mathbf{U} \times$   
 653  $\mathbf{B}$ ) electric field. It should be noted that the flow lines of the O<sup>+</sup> ions seen in Figure 11  
 654 cannot show in detail how individual planetary O<sup>+</sup> ions move, since the bulk velocity can  
 655 include ions which have very different velocities. However, the flow lines illustrate the fact  
 656 that the O<sup>+</sup> can be very non-gyro-tropic because of the large ion gyro radius, compared  
 657 with the size of the interaction region. In both the ICME  $n_{20}$ ,  $n_{12}$ , and nominal cases,  
 658 there are pick-up ions. However, only in the ICME orbit did the VEX spacecraft cross  
 659 the flow channel and provide evidence (by the ASPERA-4 instrument) of the presence  
 660 of energetic heavy ions. This is also demonstrated by the VEX observations in Figures  
 661 1 and 2 in which energized O<sup>+</sup> ions are recorded by ASPERA-4 (around 10keV). As ex-  
 662 pected, the convective electric field increases during the ICME driving conditions ( $n_{20}$ )  
 663 shown in panel (a). This is also reflected by increased O<sup>+</sup> escape during the ICME. The  
 664 escape rates for both cases are summarized in Table 2. The escape rates are computed  
 665 from the number of ions which are escaping from the simulation box. It is important to  
 666 note that in both cases, the quantity of O<sup>+</sup> production is the same since both possess the  
 667 same ionosphere and exobase. Thus, the distribution of the newly formed planetary ions  
 668 is identical. As already mentioned, the Venus ionosphere is treated as a fully conducting  
 669 obstacle, at a fixed height, so hysteresis effects are excluded, and possible effects of the  
 670 ICME on the ionosphere are also neglected. As a result, the differences in escape rates are  
 671 purely a consequence of the upstream conditions and thus, the ICME driving. From the  
 672 vales in Table 2, we estimate that during the ICME driving interval, there is approximately  
 673 a 30% increase in O<sup>+</sup> escape for the  $n_{20}$  run and 24.5% for the  $n_{12}$  run. The ICME rates  
 674 are computed relative to the nominal run.

## 675 6 Discussion

676 In this work, we have analyzed the Venus induced magnetosphere during an ICME  
 677 using observations from VEX and hybrid simulations. We compared the observed and  
 678 simulated draping patterns as a metric to determine the feasibility of modeling the Venus  
 679 solar wind interaction during ICME sheath conditions. The model results were then used  
 680 to determine the escape of planetary heavy ions (O<sup>+</sup>) resulting from the enhanced solar  
 681 wind convective electric field. We also investigated the factors leading to an extraordinary

250 nT magnetic barrier encounter. We briefly employed 32Hz VEX MAG measurements to report the presence of substantial electromagnetic wave activity spanning the interval from upstream of the bow shock through to the downstream magnetosheath.

Arguably the most striking observation on 05 November 2011 was the extremely larger magnetic barrier which exceeded 250 nT, as shown in Figures 1 and 2. In Figure 4 we plotted the normalized magnetic field profile from upstream to after the magnetic barrier into the night-side. From our analysis, there is not one clear mechanism which would drive such an atypically large magnetic barrier. However, there are several distinct factors which may contribute and eventually go to great lengths to explain this. First, the compression ratio of the shock is larger, which results in a increased downstream magnetic field strength. Second, the day-side appears to be unusually compressed, which is evidenced by the short traversal of the magnetosheath by VEX, and this is consistent with the large positive gradient of the magnetic field from downstream to the magnetic barrier. Third, the upstream conditions already consist of “shocked” plasma from the ICME sheath which is heated, dense, and contains a large magnetic field strength (determined from ASPERA-4 energy spectra). This combination of plasma parameters provides substantial external pressure driving which is physically consistent with the above interpretations. We must also take into account the duration of the ICME sheath driving, since VEX crosses the bow shock after the ICME sheath has been present for several hours. This prolonged external driving allows magnetic flux to pile up against the magnetic barrier obstacle for considerable time, which likely plays a role.

It is also noteworthy that the magnetic profile after the magnetic barrier is markedly different during the ICME passage. Our interpretation of this is that due to the larger external pressure from the ICME, the ionosphere becomes magnetized. A magnetized ionosphere occurs if the pressure balance is achieved in the collisional region (a few hundred km) due to high external pressure driving — as is the case here. In these circumstances, the magnetic field does not drop as sharply as the unmagnetized case, and instead diffuses and convects downwards towards the ionosphere (see *Futaana et al.* [2017] and references therein). Measurements of comparable magnitude magnetic barriers are extremely rare, and to our knowledge, this is the largest that VEX recorded. We believe that an explanation for such a rare observation is that (like this example) there are numerous physical and technical criteria which have to be met in order for such an event to be recorded. Out of these criteria, a period of prolonged external pressure driving and magnetic flux pile up is arguably the most important. In terms of the model results, it is important to note that the magnetic barrier was always under-estimated (compared to VEX) by the model. Between the  $n_{12}$  and  $n_{20}$  runs, the modeled barrier strength did increase, which is consistent with the hypothesis above in the sense that large external pressure contributions played a strong role in the 250nT barrier observation. We should also mention that the lack of a self-consistent ionosphere may play a role, and therefore this topic may be revised later when a more sophisticated treatment of the ionosphere and time dependent input capabilities are added to the model.

During the model-data comparison presented in Figures 6 and 7, the procedure reached an optimal solution for the entire VEX orbit during nominal conditions, suggesting the model can reproduce an accurate global draping pattern. On the contrary, during the ICME  $n_{20}$  run, the procedure converged on the day-side, but failed to do so on the night-side; the result was also the same for the  $n_{12}$  run. There are several explanations for this. First, taking into consideration the modeled draping pattern, discrepancies may be introduced partly due to the model, which does not have a self-consistent ionosphere, along with a relatively coarse spatial resolution. Second, any inaccuracies in the measured upstream conditions would play a significant role, particularly the plasma measurements, which are crucial to implementing a comparable model run. The density measured inside ICME sheath regions can vary significantly, with peaks up to  $30\text{-}60\text{ cm}^{-3}$  observed [*Das et al.*, 2011]; the highest densities in ICME sheaths are often found close to the shock and

735 ejecta and are termed Pile-Up Compression regions (PUC) [*Das et al.*, 2011]. Therefore,  
 736 the occurrence of such high-density structures could lead to the enhanced magnetic bar-  
 737 rier, and differences in the model-data comparison. This was also motivation for making  
 738 the two ICME runs with varying density. Finally, the divergence of the measured mag-  
 739 netotail is likely due to the ICME ejecta, which is visible in the magnetotail profile (also  
 740 reported by *Vech et al.* [2015]). However, according to Figure 9, and based entirely on the  
 741 ICME sheath input parameters, the simulated magnetic configuration of the magnetotail  
 742 did not appear significantly altered compared to the nominal run. It should also be noted  
 743 that in a run where the solar wind flow is not exactly along the model x-axis, the rotation  
 744 procedure also rotates the solar wind velocity vector. Therefore, the rotated solutions can-  
 745 not exactly describe similar solar wind flow situations for different IMF conditions. In the  
 746 ICME case, the upstream flow direction is approximately  $23.7^\circ$  with respect to the VSO  
 747 x-axis during the ICME sheath — any differences introduced from this small oblique flow  
 748 are excluded from these results.

749 Previous studies (e.g. *Luhmann et al.* [2008] and references therein) which inves-  
 750 tigate the simulated Venus-ICME interaction have typically focused on the ICME ejecta  
 751 component, since the evolution of the field and plasma properties occur much slower  
 752 compared to the sheath region. However, based on the good model-data solution on the  
 753 day-side (until the ICME ejecta), we conclude that it is also feasible to model the ICME  
 754 sheath conditions. Nevertheless, once a transition from the ICME sheath to the ejecta oc-  
 755 curs (see Figure 1b between 32-35 hours), any model-data comparisons from that point  
 756 are likely to diverge. We suspect this was the reason for the divergence between the model  
 757 data solution observed in R4 in Figure 6. For that reason, it is challenging to infer global  
 758 conclusions from ICME sheath and ejecta of the same event. We suggest that the best ap-  
 759 proach for such studies should be statistical that focus on individual regions separately.  
 760 Another option is to utilize models which can handle upstream transients, and this may be  
 761 revisited as the hybrid model is developed further.

762 The atypically high dynamic pressures of ICME events have many effects, namely  
 763 magnetizing the ionosphere, and reducing the altitude of the ionopause [*Luhmann and*  
 764 *Cravens*, 1991]. In some circumstances, these can potentially increase the number of plan-  
 765 etary ions which are lost. We investigated this by computing the  $O^+$  escape rates for each  
 766 of our runs. These calculations resulted in 30.5% and 24.5% increases (with respect to  
 767 the nominal run) of  $O^+$  escape for the  $n_{20}$  and  $n_{12}$  ICME sheath runs, respectively. In a  
 768 similar study, *Luhmann et al.* [2008] concluded that from four examined ICMEs, in only  
 769 one case, could they report increases in  $O^+$  escape flux. However, it is important to keep  
 770 in mind that their cases were ICME ejecta driven, which typically have lower densities  
 771 compared to our ICME sheath case. We investigated the role of density in Table 2, which  
 772 showed elevated  $O^+$  for a larger upstream density. This conclusion is consistent with that  
 773 of *Liu et al.* [2009] who, reported a similar relationship. These results are indicative of  
 774 variable  $O^+$  escape rates for sheath and ejecta conditions in which the value is larger for  
 775 the sheath region. A likely cause of this is the generally higher densities during the ICME  
 776 sheaths. On the other hand, these regions present more challenging conditions from a  
 777 modeling standpoint. We should also reiterate that the ionosphere is kept constant between  
 778 each run, meaning that any impact of the ICME on the ionosphere is neglected. For that  
 779 reason, any quoted escape rates are purely a response from upstream conditions. In addi-  
 780 tion, *Liu et al.* [2009] reported that “the IMF x component enhances the  $O^+$  escape rate”.  
 781 This is important to note, as our model did not include upstream transients, and indeed,  
 782 cannot introduce transients in the IMF  $B_x$  component. Therefore, any effects from tran-  
 783 sient IMF  $B_x$  behavior are excluded from these results. It would be a worthwhile endeavor  
 784 for future investigators who have the capability to introduce transient upstream conditions  
 785 to quantify this effect in more detail.

786 Finally, the 32Hz resolution VEX MAG data exhibited clear wave activity upstream  
 787 and downstream of the bow shock front. Based on our analysis, we concluded that these

upstream fluctuations are likely dispersive whistler precursors associated with the bow shock which help to balance the shock front steepening [Kennel *et al.*, 1985]. Very similar 1Hz waves were reported by *Orlowski and Russell* [1991] in the Venus foreshock who also suggested they could be whistler mode waves generated at the bow shock. This generation mechanism and wave properties are comparable to numerous observations upstream of the terrestrial bow shock [Fairfield, 1974] and other planetary bow shocks [Russell, 2007]. It is also worth mentioning that ion cyclotron waves were observed upstream of the bow shock by *Delva et al.* [2008]. However, the wave properties we observe are more consistent with the whistler mode. Regarding the downstream waves, these contained relatively large amplitudes ( $|\mathbf{B}_{RMS}|/\langle|\mathbf{B}|\rangle \sim 20\%$ ). Their period is approximately one second, placing them slightly below the local ion gyro-frequency. A possible candidate for these are ion-cyclotron waves which can be generated by the ion pick-up process [Russell *et al.*, 2006]. However, since we were unable to determine the expected parallel propagation, we conclude that these may be whistler waves originating upstream. This is supported by the similar polarization (see Figure 5) and propagation angle. It is also worth noting that whistler waves were observed until the shock ramp and inside the foot region which exhibited extremely similar characteristics (not shown). We should also mention that Venus magnetosheath turbulence has been attributed to the bow shock itself. We ruled these out since these variations were associated with a quasi-parallel bow shock and possess periods of 10-40s [Luhmann *et al.*, 1983; Du *et al.*, 2009], which are significantly below what we observed. It is difficult to determine the role of the observed waves in the ICME-Venus interaction, for which more work and event studies are required. Nevertheless, their occurrence is worth reporting, as it clearly demonstrates that future investigators should also consider small scale structures close to, and above the local gyro-frequency when studying similar events. In addition, to describe these complex non-linear effects, models will need the appropriate resolution in order to resolve ion-scale effects.

## 7 Summary and Conclusions

We can summarize the main results of this study as follows:

1. We have studied the properties and the response of the Venus induced magnetosphere in the extreme case when the planet was embedded inside an ICME, and when atypically high magnetic field values ( $\sim 250$  nT) were observed.
2. Numerous factors may have resulted in an extremely large magnetic barrier and the prolonged external pressure driving and magnetic flux pile-up seem likely to play a dominant role.
3. During the ICME passage, VEX MAG data suggested the ionosphere became magnetized, and the bow shock moved closer to the planet whereas the effect on the magnetic barrier location was negligible.
4. Global large-scale analysis based on 3D hybrid model simulations suggest that the magnetic field draping pattern during the ICME sheath passage was much alike during the nominal solar wind conditions. The simulation was found to reproduce the magnetic field draping pattern on the day-side relative well, but poorly on the night-side. This is likely the result of the upstream conditions changing from the sheath to ejecta. Moreover, upstream ICME sheath conditions resulted in around a 30% increase in the total  $O^+$  escape rate.
5. This study has demonstrated that hybrid simulation runs are also applicable to extreme ICME cases, even when the upstream conditions are highly dynamic. Having said that, one has to err on the side of caution, as model-data solutions diverge once the ICME state changes.
6. The analysis of the small spatial scale and fast phenomena made by high resolution magnetic field observations showed that during the ICME passage, large amplitude upstream and downstream waves were observed. The waves cannot be character-

839 ized unambiguously, but are likely to be whistler waves convected from upstream to  
840 downstream.

841 To conclude, both experimental data and hybrid numerical simulations have demon-  
842 strated that the Venesian plasma environment can be significantly altered during extreme  
843 driving events such as ICMEs. However, to fully understand the extent of these interac-  
844 tions, both data and numerical models are required to infer global effects such as O<sup>+</sup> es-  
845 cape rates. This work has shed some light on various aspects of these interactions, but  
846 also open questions remain. While our results suggest that the O<sup>+</sup> escape rates are ele-  
847 vated for ICME sheath conditions, it is still unclear if similar escape rates can be quoted  
848 for the ICME ejecta part. This will likely require future studies using many events and uti-  
849 lizing numerical models. Fortunately, the extensive Venus Express catalog contains many  
850 ICME-Venus encounters. Another important aspect is the presence, and role of electro-  
851 magnetic waves during Venus-ICME interactions, whose roles are not fully understood.  
852 A large scale statistical study of their properties and potential consequences is also war-  
853 ranted. One main point to take away from this work is that it is indeed feasible to model  
854 the dynamic ICME sheath intervals, but one should carefully consider the upstream time-  
855 dependant conditions since model-data comparisons diverge once the upstream conditions  
856 switch to the ICME ejecta. Understanding the conditions and physical mechanisms which  
857 result in large magnetic barriers is also important, and a follow-up study on many more  
858 (albeit less extreme) events, is justified. In addition, these results are also applicable and  
859 of interest to other planetary bodies. Although other planets differ in terms of composi-  
860 tion, intrinsic magnetic field, and chemistry, they often contain surprisingly similar regions  
861 and boundaries which are heavily affected by ICME passages. Finally, with increasing  
862 complexity and performance of numerical models, future studies should focus on mod-  
863 eling such interactions in greater detail by including turbulence and variation of plasma  
864 and field properties intrinsic to ICME sheaths, with a more sophisticated treatment of the  
865 ionosphere, which evidently is affected.

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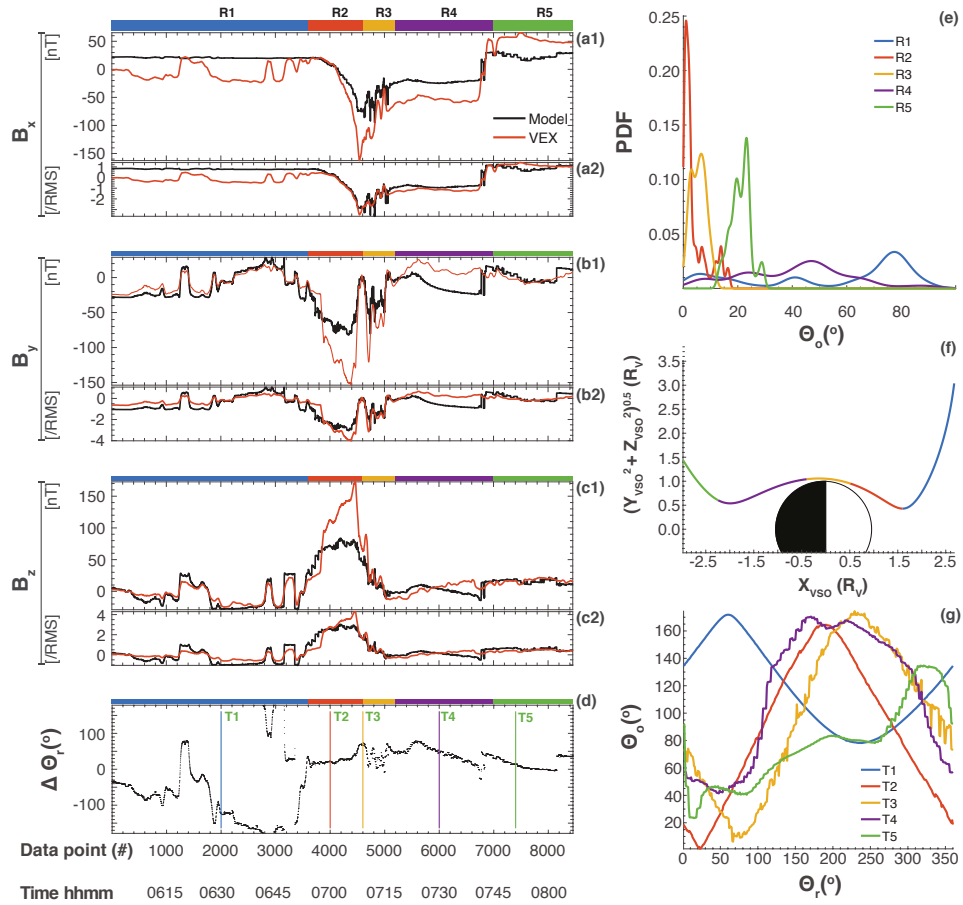
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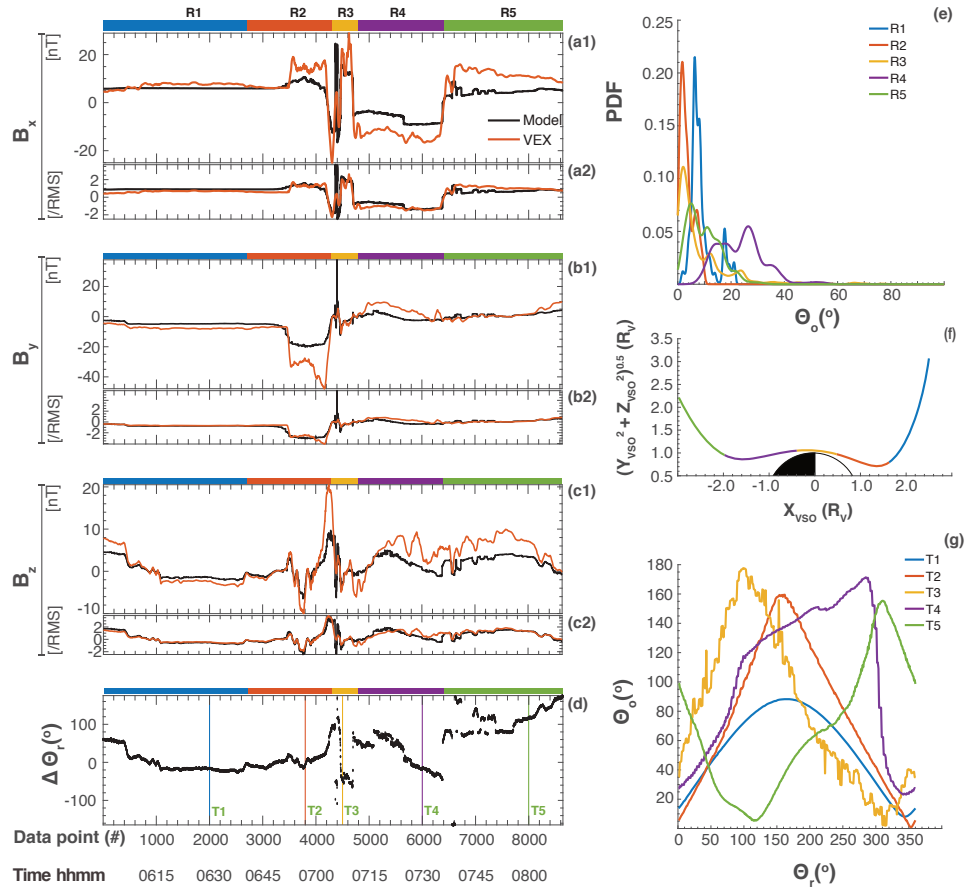
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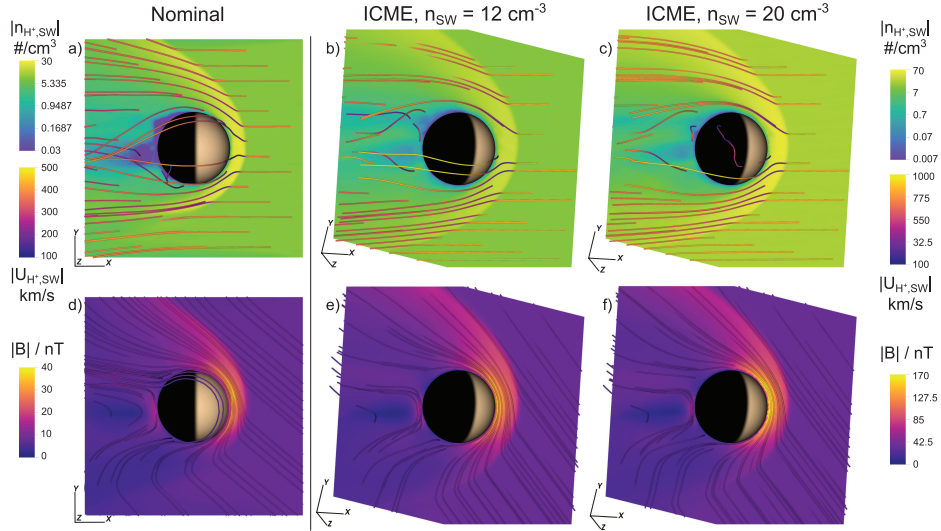
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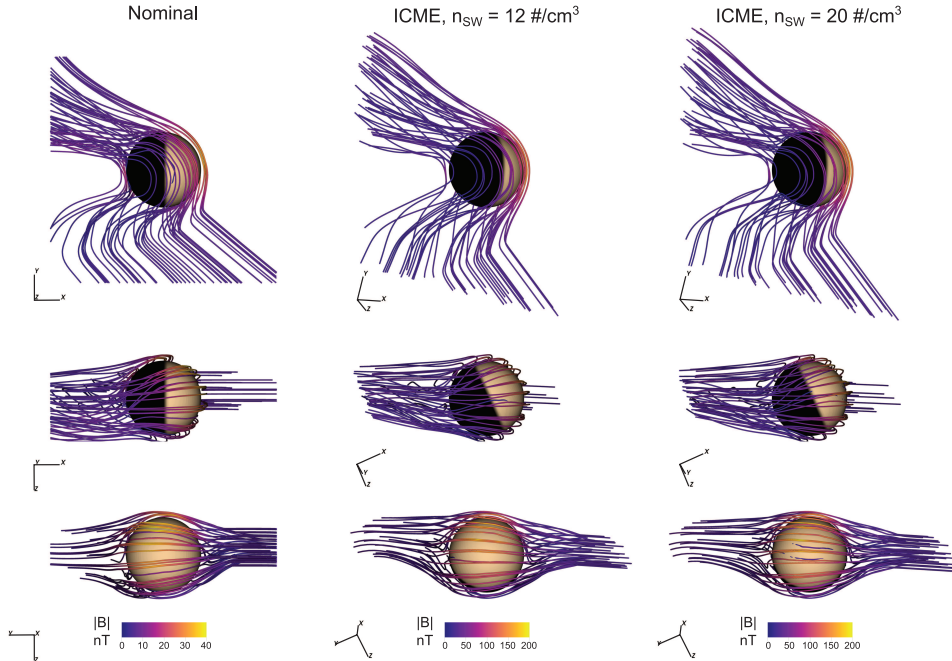
467 **Figure 6.** Comparison between the VEX and the hybrid model data during the clock angle optimization  
 468 procedure for the date 05 November 2011. Panels (a-c) show the VEX-model time series comparison for  
 469 each magnetic field component. The first sub-panels 1 (e.g. a1) indicate the actual field values in nT, whereas  
 470 subscript 2 refers to the fields normalized by the RMS computed over the entire interval (/RMS). The bot-  
 471 tom panel (d) shows the angle of rotation about the x-axis required to achieve the optimal angle between the  
 472 modeled and observed field directions. The five different colors correspond to the following regions (R1-5):  
 473 upstream, bow shock to magnetic barrier maximum, periapsis, magnetotail until cross-tail tail current sheet  
 474 and magnetotail after cross-tail current sheet. Panel (e) shows PDFs of the angles between the model and  
 475 VEX field direction for each point after the rotation (i.e. low angles indicate a good agreement). Panel (f)  
 476 indicates where each region was during the VEX orbit. Panel (g) shows the optimal angle vs the yz plane rota-  
 477 tion angle for the times (T1-5) labeled in panel (d). In effect, panel (g) shows an example of how the optimal  
 478 angle changes with the rotation angle. It can be seen that in some regions a good optimal angle is achieved  
 479 (T2) but in other cases a solution was not reached (T5).



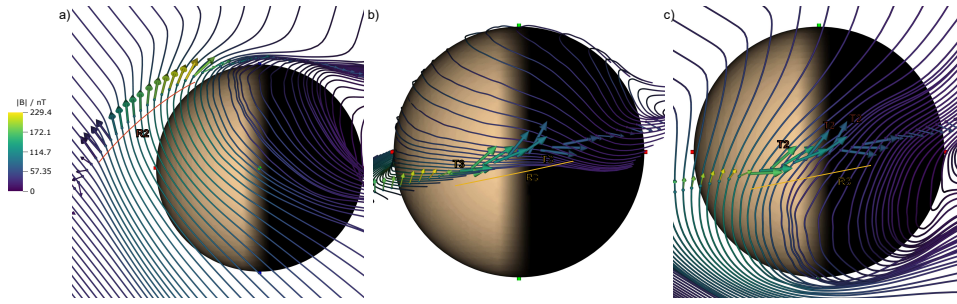
516 **Figure 7.** Comparison between the VEX and hybrid model data after the clock angle optimization procedure for a nominal day on 29/10/2011. The format is the same as Figure 6.  
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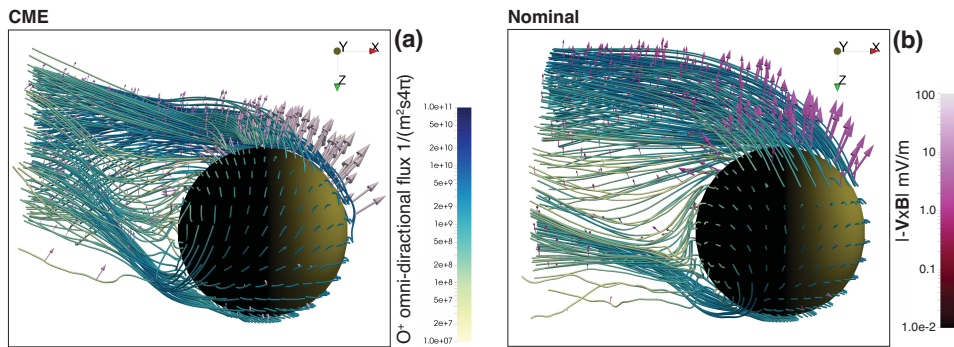
532 **Figure 8.** Comparison of the Venus plasma environment for the (left column) nominal run, and the ICME  
 533 driving conditions (middle and right column). The data is presented on a plane spanned by the solar wind  
 534 velocity and IMF vectors. The color scales for the nominal case are displayed on the left, while the ICME  
 535 color scales are given on the right. Note that the ICME color scales are identical, but different from the nom-  
 536 inal. The top row gives the density of solar wind on the slice color and solar wind streamlines superposed,  
 537 with streamline propagation initiated from the slice plane. The bottom row slice and field line colors give the  
 538 magnetic field magnitude on the slice and on the field lines connected to the slice.



556 **Figure 9.** Magnetic field lines and solar wind flow lines for the nominal (left column) and ICME (middle  
 557 and right column) conditions. The model data is presented in an aberrated system to reduce asymmetries  
 558 introduced from oblique solar wind flow. The color on the magnetic field line gives the value of the magnetic  
 559 field at each position along the line. The color scales for each column are given on the bottom; the scales are  
 560 identical for the ICME cases and reduced for the nominal case.



598 **Figure 10.** Left to right (R2 at T2, R3 at T3, and R3 at T2) VEX MAG measurements (vectors) and  
 599 changes in magnetic morphology with respect to clock angle optimizations, as inferred from the simulation  
 600 (field lines). Please see figure 6 for descriptions of these regions (R) and times (T). Observations at the  
 601 region of interest in each sub-figure are highlighted with large vector symbols, with the color denoting mag-  
 602 netic field magnitude for both field lines and the observations, at the same scale. The figures illustrate that R3  
 603 potentially contains magnetic fields from two separate origins. Left: R2 (including the magnetosheath and the  
 604 magnetic barrier), with the corresponding rotation of simulated magnetic field. As in 6, the correspondence  
 605 in magnetic field orientation is good and relatively stable. Center: R3 (post-barrier) magnetic morphology, as  
 606 given by the clock angle optimization procedure for the corresponding time interval. Points of good magnetic  
 607 correspondence to the optimized rotation are marked in the figure with T3; the morphology in the simulation  
 608 at this rotation corresponds to equatorial draping. Right: R3 magnetic morphology, as given by the clock  
 609 angle optimization to R2 (magnetosheath and barrier), i.e. the simulation magnetic field is the same as in  
 610 the leftmost plot. Points of good correspondence are marked with T2 in the sub-figure. The morphology  
 611 corresponds to draping close to the "pole" of the induced magnetosphere.



641 **Figure 11.** Planetary  $O^+$  streamlines for (a) ICME and (b) nominal driving conditions. The color of each  
 642 streamline indicates the omni-directional flux which was started close to the exobase. Directions of each ar-  
 643 row corresponds to the convective electric field,  $\mathbf{E}$ , and the color is the magnitude. Note the increase of  $|\mathbf{E}|$   
 644 for the ICME case, which is reflected by a 30% increase in  $O^+$  escape.