

Supporting Information for "A Survey of Venus Shock Crossings Dominated by Kinematic Relaxation"

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1. Figures S1 to S7
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Introduction

The supporting information includes figures showing the profile of the magnetic field magnitude and tables of the key calculated parameters for all of shock crossings identified in this study for time intervals when Venus Express detects the magnetic cloud phase of an interplanetary coronal mass ejection (ICME). A subset of the magnetic field profiles and calculated parameters for the shock crossings is included in the main paper. The shock crossings are grouped into one of six Figures S1 to S6 and Tables S1 to S6 based on the ICME magnetic cloud date. Within each figure and table the shock crossings are grouped into subsets based on the detection of a sequence of shock crossings over a short time interval. Detailed information for each set of crossings is included in the caption for each figure.

The supporting information also includes Tables S7 to S10, which contain the upstream magnetic field and plasma data used to calculate the Alfvén Mach number and plasma β for shock crossings on four of the days studied. Detailed information about the measurement interval used for each set of shock crossings is included in the table captions.

Finally, the supporting information includes Table S11 which contains the list of shock crossings used to determine the bow shock location models at seven different Alfvén Mach numbers and Table S12 which contains the resulting parameters (eccentricity ϵ and terminator altitude L_T) for the conic section model given in Eq. (1). Figure S7 plots the location of these models in relation to the surface of Venus, together with the conic section model previously derived by Zhang et al. (2008) for solar minimum.

$$A_m = \frac{L_T}{1 + \epsilon \cos(SZA)} \quad (1)$$

References

- Zhang, T. L., Delva, M., Baumjohann, W., Volwerk, M., Russell, C., Barabash, S., ...
 Zambelli, W. (2008). Initial Venus Express magnetic field observations of the Venus
 bow shock location at solar minimum. *Planetary and Space Science*, 56(6), 785–789.
 doi: 10.1016/j.pss.2007.09.012

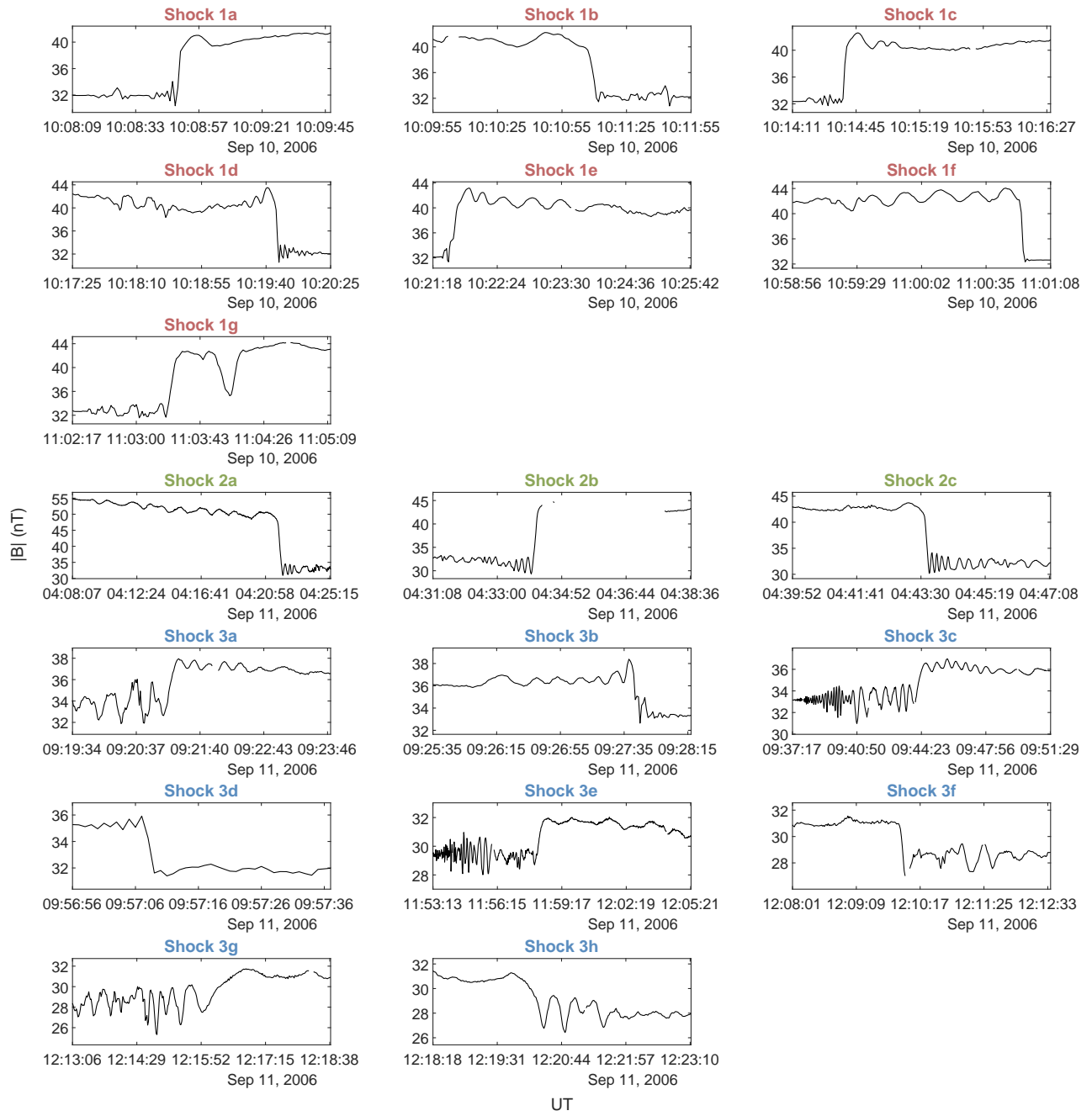


Figure S1. Venus Express magnetic field magnitude plotted for separate intervals showing the individual shock crossings on 10th-11th September 2006 for each of the three colored regions highlighted in Figure 1a of the main paper. The different colored plot titles indicate which of the regions each of the shock crossings belong. For clarity of presentation, the limits of both the time and magnetic field axes are set independently for each panel.

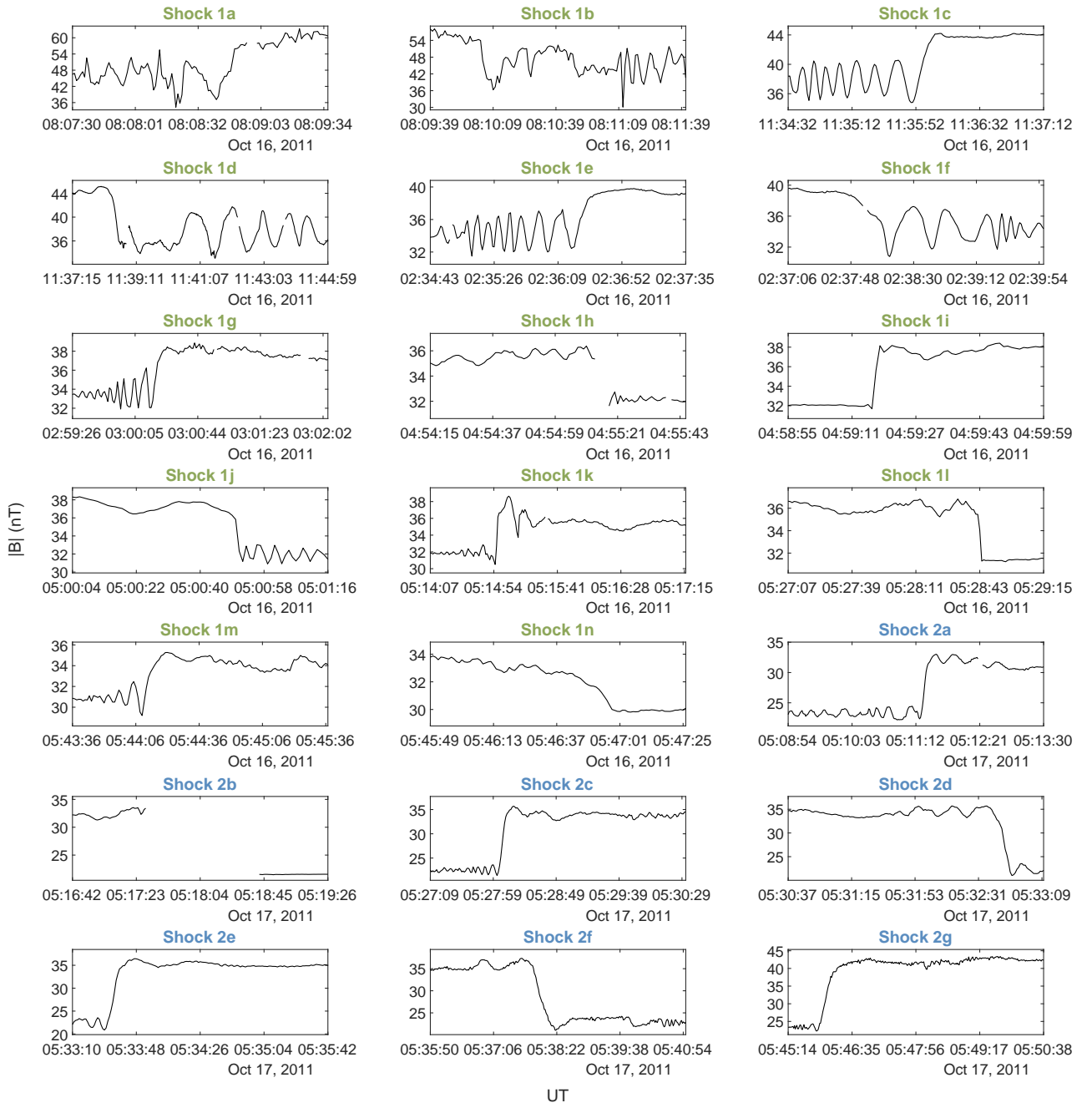


Figure S2. Venus Express magnetic field magnitude plotted for separate intervals showing the individual shock crossings on 16th-17th October 2011 for each of the two regions highlighted in Figure 1b of the main paper. The different colored plot titles indicate which of the regions each of the shock crossings belong. For clarity of presentation, the limits of both the time and magnetic field axes are set independently for each panel.

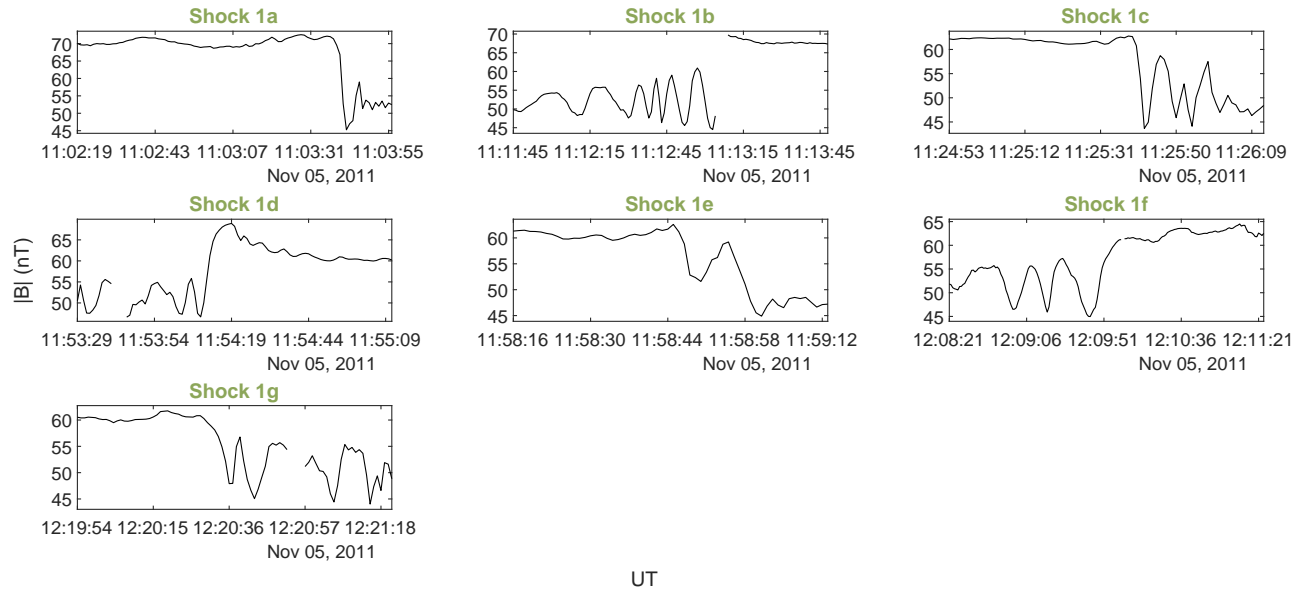


Figure S3. Venus Express magnetic field magnitude plotted for separate intervals showing the individual shock crossings on 5th November 2011 for the green region highlighted in Figure 1c of the main paper. For clarity of presentation, the limits of both the time and magnetic field axes are set independently for each panel.

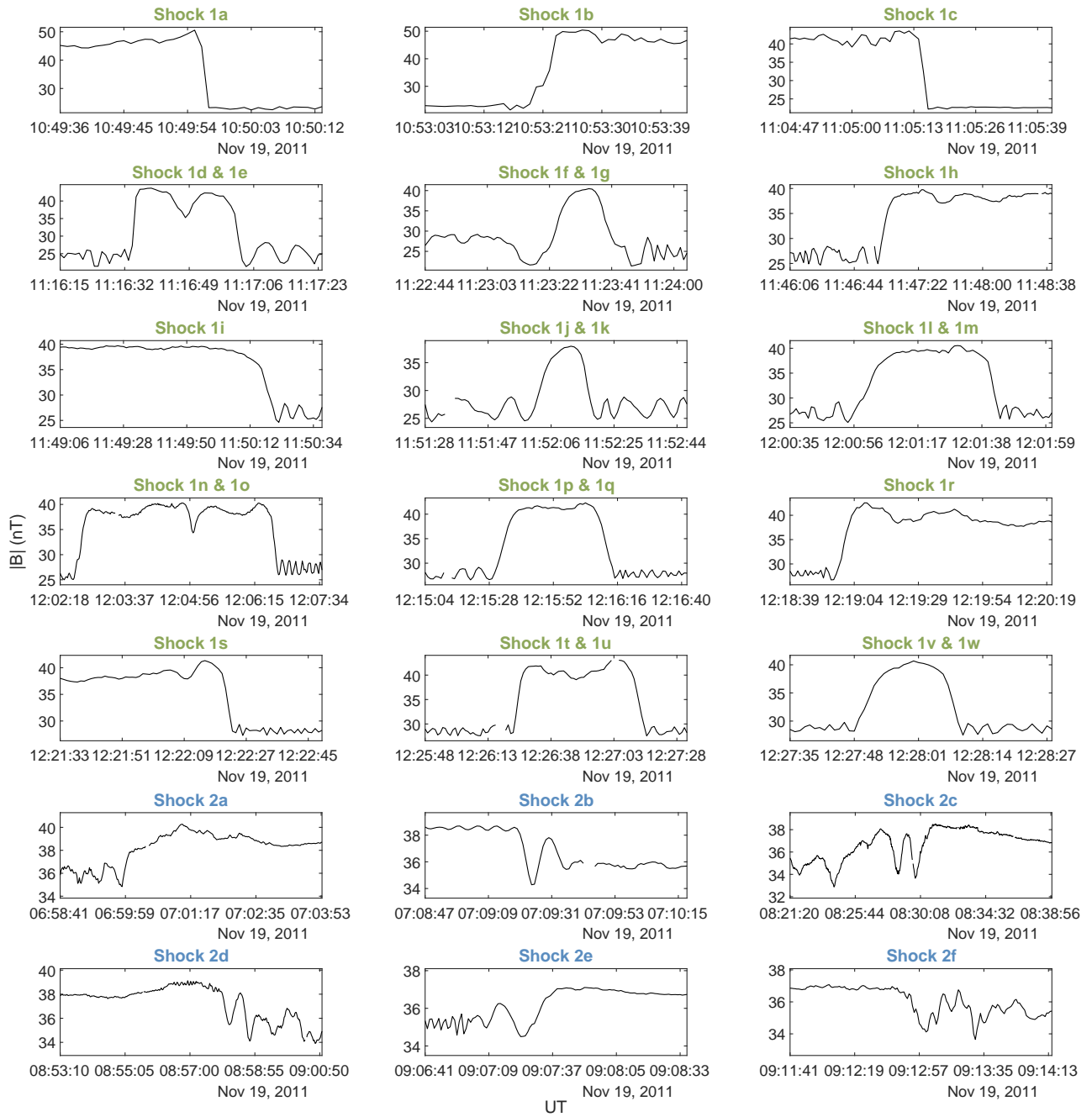


Figure S4. Venus Express magnetic field magnitude plotted for separate intervals showing the individual shock crossings on 19th November 2011 for each of the two colored regions highlighted in Figure 1d of the main paper. The different colored plot titles indicate which of the regions each of the shock crossings belong. For clarity of presentation, the limits of both the time and magnetic field axes are set independently for each panel and two shock crossings are shown on some panels due to the short downstream interval.

May 22, 2020, 2:33pm

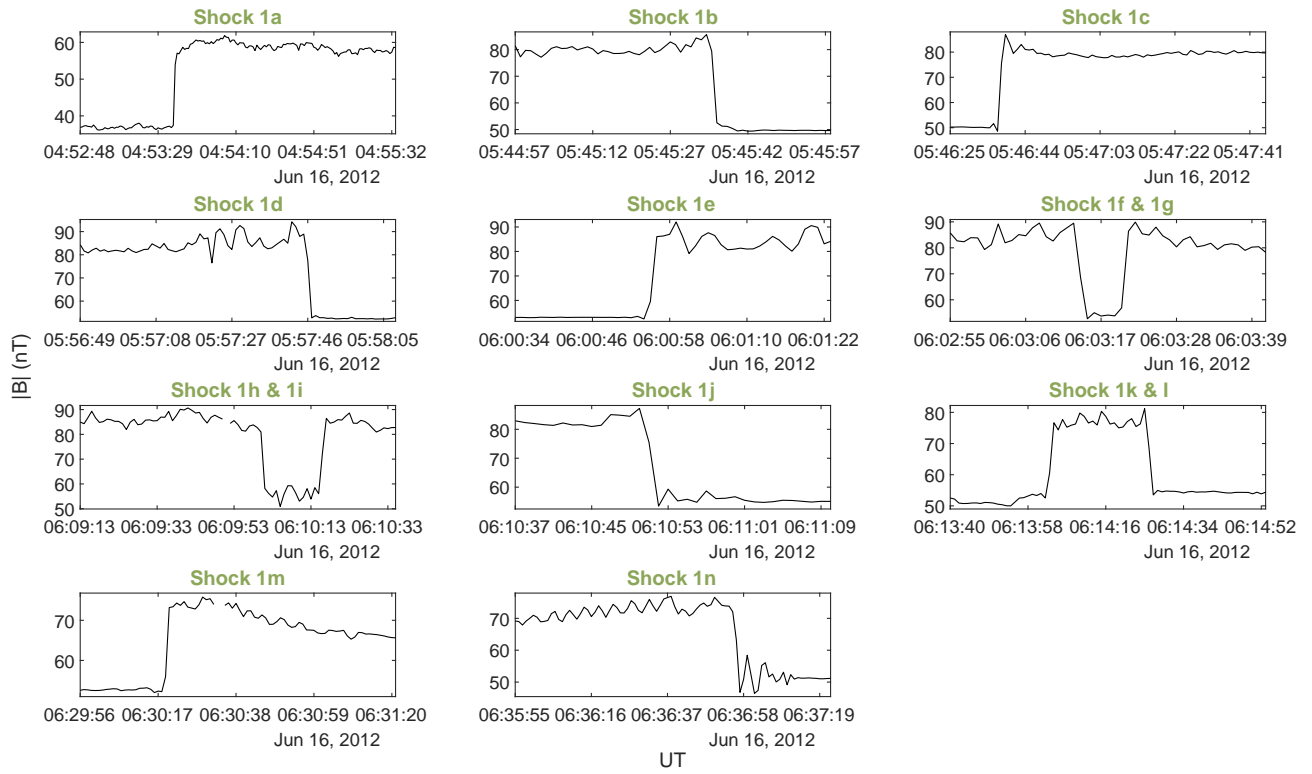


Figure S5. Venus Express magnetic field magnitude plotted for separate intervals showing the individual shock crossings on 16th June 2012 for the green region highlighted in Figure 1e of the main paper. For clarity of presentation, the limits of both the time and magnetic field axes are set independently for each panel and two shock crossings are shown on some panels due to the short upstream/downstream interval.

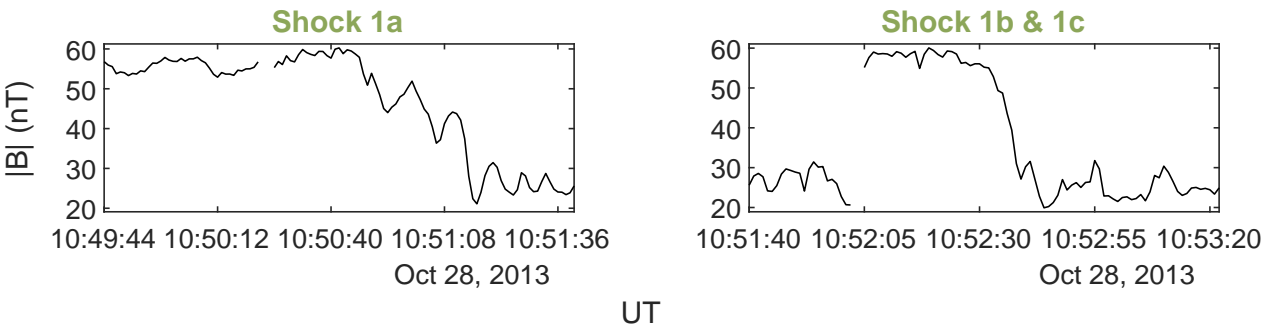


Figure S6. Venus Express magnetic field magnitude plotted for separate intervals showing the individual shock crossings on 28th October 2013 for the green region highlighted in Figure 1f of the main paper. For clarity of presentation, the limits of both the time and magnetic field axes are set independently for each panel and two shock crossings are shown on some panels due to the short downstream interval.

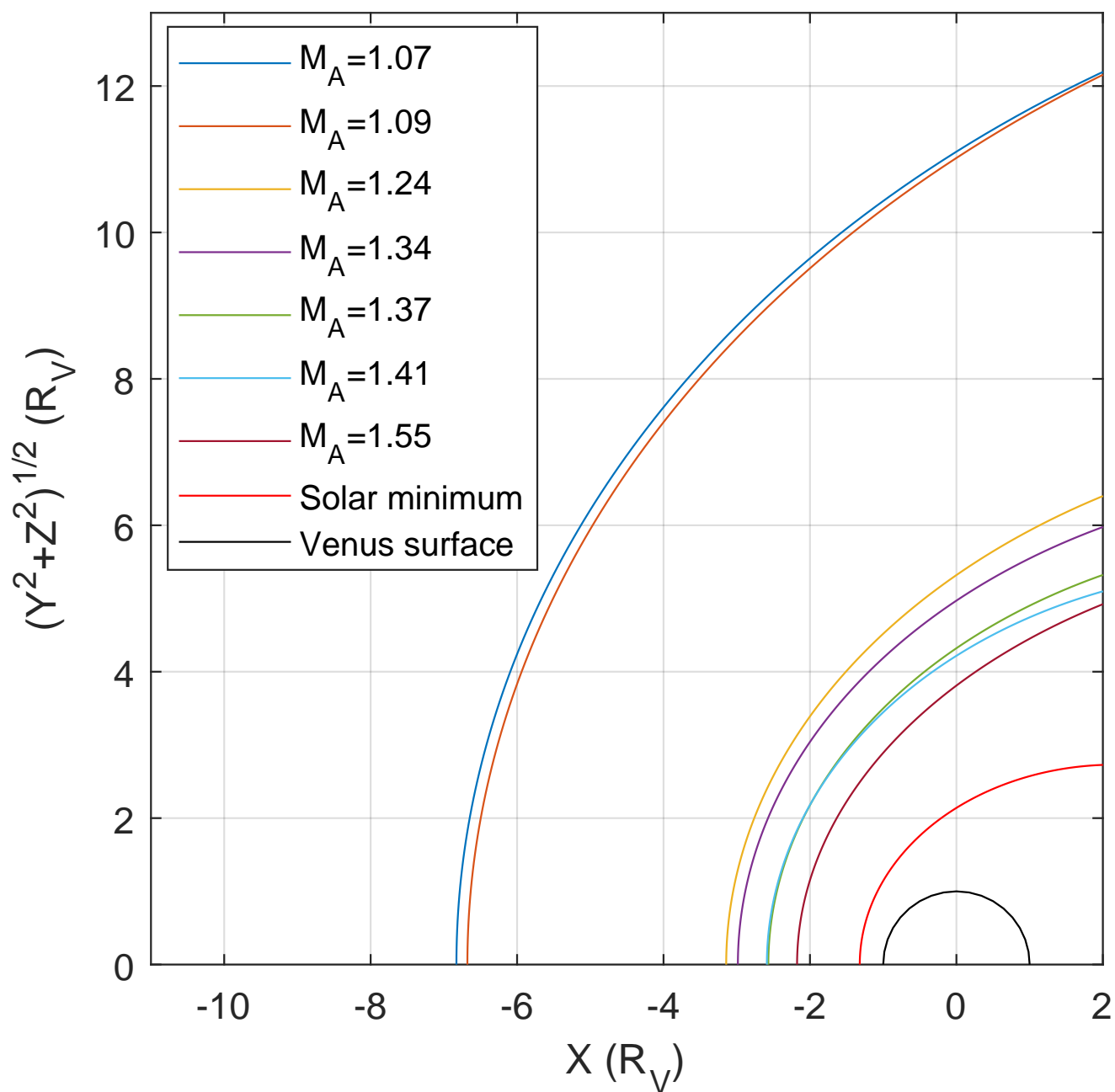


Figure S7. Bow shock location with respect to the surface of Venus for the models determined for seven different Alfvén Mach numbers and the previously determined solar minimum model (Zhang et al., 2008).

Table S1. Magnetic field derived parameters for the three groups of Venus bow shock crossings detected in Venus Express data on the 10-11th September 2006.

Shock	$\theta_{B,n_{mv}}$ ($^{\circ}$)	$\theta_{B,n_{cp}}$ ($^{\circ}$)	$M_{A,B}$	SZA ($^{\circ}$)	A (R_V)	A_m (R_V)
1a	76	70	1.20	112	9.40	2.79
1b	79	79	1.20	113	9.40	2.83
1c	78	63	1.19	113	9.30	2.83
1d	84	83	1.19	113	9.30	2.83
1e	87	70	1.22	113	9.20	2.83
1f	82	80	1.23	116	8.60	2.94
1g	79	78	1.22	116	8.60	2.94
2a	72	71	1.37	40	2.78	1.45
2b	72	76	1.27	45	3.27	1.49
2c	75	51	1.24	49	3.63	1.52
3a	70	49	1.07	81	9.72	1.95
3b	85	63	1.07	82	9.80	1.97
3c	68	64	1.07	82	10.00	1.97
3d	77	53	1.09	83	10.20	1.99
3e	54	47	1.06	88	11.30	2.09
3f	74	54	1.07	89	11.30	2.12
3g	58	55	1.07	89	11.40	2.12
3h	64	64	1.06	89	11.40	2.12

Table S2. Magnetic field derived parameters for the Venus bow shock crossings detected in

Venus Express data on the 16-17th October 2011.

Shock	$\theta_{B,n_{mv}}$ ($^{\circ}$)	$\theta_{B,n_{cp}}$ ($^{\circ}$)	$M_{A,B}$	SZA ($^{\circ}$)	$A (R_V)$	$A_m (R_V)$
1a	30	26	1.18	123	4.77	3.23
1b	30	21	1.17	123	4.81	3.23
1c	45	52	1.11	108	9.21	2.65
1d	50	42	1.17	108	9.25	2.65
1e	63	63	1.11	101	11.17	2.43
1f	65	67	1.11	101	11.18	2.43
1g	86	62	1.11	101	11.34	2.43
1h	77	58	1.08	97	11.87	2.32
1i	83	42	1.12	97	11.88	2.32
1j	84	70	1.12	97	11.89	2.32
1k	78	43	1.09	97	11.92	2.32
1l	80	64	1.11	96	11.95	2.29
1m	80	66	1.09	96	11.97	2.29
1n	57	11	1.05	96	11.98	2.29
2a	72	71	1.24	59	3.90	1.62
2b	76	68	1.33	58	3.68	1.61
2c	66	65	1.37	55	3.29	1.58
2d	81	72	1.37	54	3.11	1.57
2e	67	68	1.40	54	3.08	1.57
2f	75	68	1.36	52	2.90	1.55
2g	74	69	1.56	50	2.57	1.53

Table S3. Magnetic field derived parameters for the Venus bow crossings detected in Venus

Express data on the 5th November 2011.

Shock	$\theta_{B,n_{mv}}$ ($^{\circ}$)	$\theta_{B,n_{cp}}$ ($^{\circ}$)	$M_{A,B}$	SZA ($^{\circ}$)	$A (R_V)$	$A_m (R_V)$
1a	58	62	1.26	123	7.79	3.23
1b	15	46	1.22	122	7.97	3.19
1c	45	30	1.17	121	8.21	3.15
1d	61	50	1.17	119	8.70	3.06
1e	13	11	1.15	119	8.77	3.06
1f	47	39	1.15	118	8.95	3.02
1g	54	67	1.15	117	9.11	2.98

Table S4. Magnetic field derived parameters for the Venus bow shock crossings detected in

Venus Express data on the 19th November 2011.

Shock	$\theta_{B,n_{mv}}$ ($^{\circ}$)	$\theta_{B,n_{cp}}$ ($^{\circ}$)	$M_{A,B}$	SZA ($^{\circ}$)	$A (R_V)$	$A_m (R_V)$
1a	66	65	1.66	130	6.75	3.56
1b	76	60	1.68	130	6.83	3.56
1c	78	83	1.54	128	7.09	3.46
1d	64	58	1.44	127	7.34	3.42
1e	72	68	1.46	127	7.35	3.42
1f	70	62	1.30	126	7.48	3.37
1g	70	56	1.43	126	7.48	3.37
1h	67	63	1.32	124	7.94	3.28
1i	77	71	1.33	124	8.01	3.28
1j	66	60	1.29	124	8.04	3.28
1k	67	62	1.29	124	8.04	3.28
1l	66	68	1.34	123	8.20	3.23
1m	74	70	1.34	123	8.22	3.23
1n	70	71	1.32	123	8.23	3.23
1o	78	70	1.29	123	8.30	3.23
1p	77	75	1.35	122	8.46	3.19
1q	76	73	1.35	122	8.47	3.19
1r	72	73	1.30	122	8.52	3.19
1s	83	73	1.27	121	8.58	3.15
1t	74	73	1.31	121	8.64	3.15
1u	80	74	1.30	121	8.66	3.15
1v	85	77	1.30	121	8.67	3.15
1w	82	79	1.30	121	8.67	3.15
2a	48	41	1.05	101	11.97	2.43
2b	77	55	1.06	101	11.98	2.43
2c	60	39	1.03	98	11.99	2.34
2d	45	33	1.06	96	11.95	2.29
2e	35	2	1.01	96	11.93	2.29
2f	46	20	1.02	96	11.92	2.29

Table S5. Magnetic field derived parameters for the Venus bow shock crossings detected in Venus Express data on the 16th June 2012.

Shock	$\theta_{B,n_{mv}}$ ($^{\circ}$)	$\theta_{B,n_{cp}}$ ($^{\circ}$)	$M_{A,B}$	SZA ($^{\circ}$)	$A (R_V)$	$A_m (R_V)$
1a	83	77	1.44	137	5.43	3.92
1b	85	80	1.47	130	6.75	3.56
1c	78	84	1.41	130	6.77	3.56
1d	77	75	1.40	129	7.03	3.51
1e	84	85	1.42	128	7.09	3.46
1f	88	81	1.40	128	7.14	3.46
1g	85	84	1.38	128	7.15	3.46
1h	73	71	1.39	127	7.29	3.42
1i	86	78	1.37	127	7.29	3.42
1j	63	68	1.34	127	7.31	3.42
1k	86	82	1.36	127	7.37	3.42
1l	80	68	1.30	127	7.38	3.42
1m	76	86	1.28	125	7.70	3.32
1n	78	79	1.24	125	7.83	3.32

Table S6. Magnetic field derived parameters for the Venus bow shock crossings detected in

Venus Express data on the 28th October 2013.

Shock	$\theta_{B,n_{mv}}$ ($^{\circ}$)	$\theta_{B,n_{cp}}$ ($^{\circ}$)	$M_{A,B}$	SZA ($^{\circ}$)	A (R_V)	A_m (R_V)
1a	61	53	1.70	114	4.20	2.86
1b	54	57	1.85	114	4.24	2.86
1c	62	55	1.80	114	4.26	2.86

Table S7. Measured and calculated upstream parameters for the second and third group of Venus bow shock crossings detected in Venus Express data on 10th-11th September 2006. All values are for protons (unless otherwise indicated), calculated as averages for the upstream u regions (unless otherwise stated) and vectors are in VSO coordinates. The upstream region for the second group is the plasma data with excellent quality flags in-between the first and second shock and for the third group it is the plasma data collected in the magnetic cloud approximately 3 hours after the last shock crossing in this group. * The proton temperature and consequently the calculated β for the second group of shocks is given as a range due to the high variance of the measurements across the time interval of these shocks.

Parameter	Shock group 2	Shock group 3
\mathbf{B}_u (nT)	[-1.6, -20.4, -25.7]	[8.0, 11.3, -15.4]
B_u (nT)	32.9	20.7
\mathbf{V}_u (km/s)	[-349, -1, 62]	[-315, -8, 17]
V_u (km/s)	354	315
n_u (cm ⁻³)	2.5	4.1
T_u (eV)	5-14 *	5.8
$V_{a,u}$ (km/s)	457	223
$\beta_{bo,u}$	0.02-0.03	0.08

Table S8. Measured and calculated upstream parameters for shock crossing 2c, 2f and 2g detected in Venus Express data on 16-17th October 2011. All values are for protons (unless otherwise indicated), calculated as averages for the upstream u regions (unless otherwise stated) and vectors are in VSO coordinates.

Parameter	Shock 2c	Shock 2f	Shock 2g
\mathbf{B}_u (nT)	[-0.9, 15.3, -16.4]	[-2.4, -15.2, -18.0]	[-2.5, 12.8, -19.3]
B_u (nT)	22.5	23.7	23.3
\mathbf{V}_u (km/s)	[-414, -77, 119]	[-408, -84, 107]	[-408, -84, 107]
V_u (km/s)	437	430	430
n_u (cm ⁻³)	2.2	3.9	3.9
T_u (eV)	28.5	19.7	19.7
$V_{a,u}$ (km/s)	330	263	259
$\beta_{bo,u}$	0.08	0.10	0.10

Table S9. Measured and calculated upstream parameters for shock crossing 2f detected in Venus Express data on 19th November 2011. All values are for protons (unless otherwise indicated) and calculated as averages for the upstream u regions (unless otherwise stated).

Parameter	Shock 2f
B_u (nT)	35.6
V_u (km/s)	617
n_u (cm ⁻³)	0.6
T_u (eV)	173
$V_{a,u}$ (km/s)	986
$\beta_{bo,u}$	0.04

Table S11. List of shock crossings used to fit the conic section bow shock model for each

Alfvén Mach number considered.

M_A	Shock list
1.07	10-11th September 2006
	3a, 3b, 3c, 3e, 3f, 3g, 3h
	19th November 2011
	2b, 2d
1.09	10-11th September 2006
	3d
	16-17th October 2011
	1f, 1k, 1m
1.24	10-11th September 2006
	1f, 2c
	16-17th October 2011
	2a
	16th June 2012
1.34	1n
	16-17th October 2011
	2b
	19th November 2011
	1i, 1l, 1m
1.37	16th June 2012
	1j
	10-11th September 2006
	2a
	16-17th October 2011
1.41	2c, 2d, 2f
	16th June 2012
	1i, 1k
	17th October 2011
	2e
1.55	16th June 2012
	1c, 1d, 1f
	16-17th October 2011
	2g
	19th November 2011
	1c

Table S12. Parameters for the conic section bow shock model determined for each Alfvén Mach number considered.

M_A	Eccentricity (ε)	Terminator Altitude (L_T)
1.07	0.626	11.1
1.09	0.650	11.0
1.24	0.692	5.32
1.34	0.666	4.97
1.37	0.682	4.32
1.41	0.629	4.22
1.55	0.751	3.81