A Study of Kinematic Relaxation at the Venus Bow Shock

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- Previous observations at Venus and the Earth – “Kinematic” shocks
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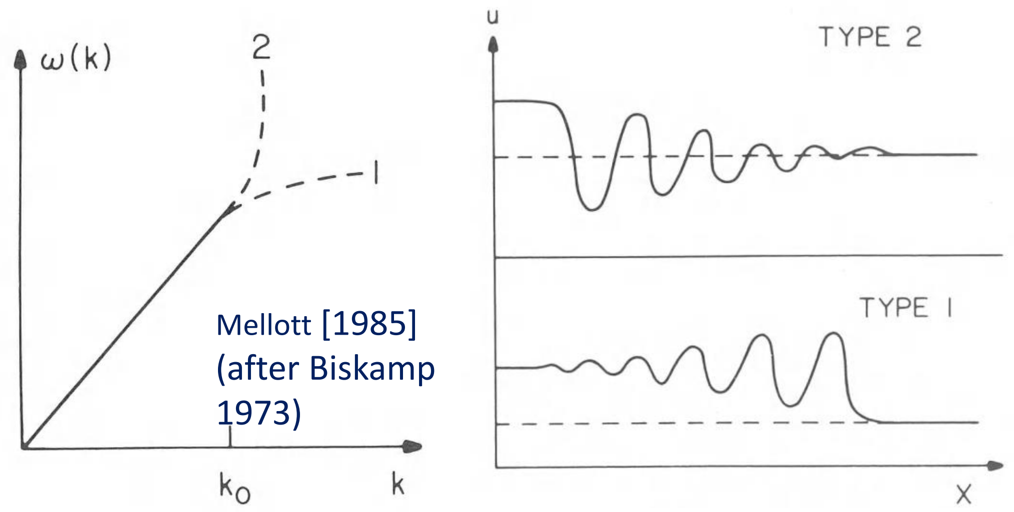
“Classical” sub-critical shocks ($\theta_{B,n} > 45$)

Dispersive:

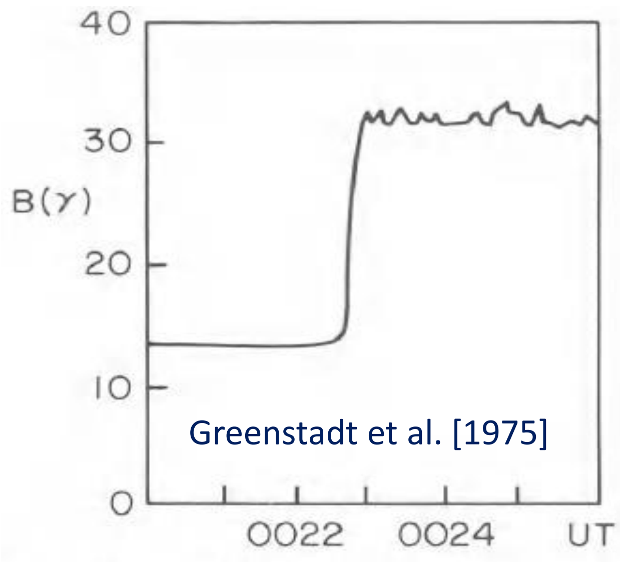
- Type 1 – downstream B oscillations (perpendicular)
- Type 2 – upstream B oscillations (quasi-perpendicular)



Mellott [1985] (after Biskamp 1973)

Resistive:

- No oscillations in B ahead of ramp
- Smooth transition to the downstream region

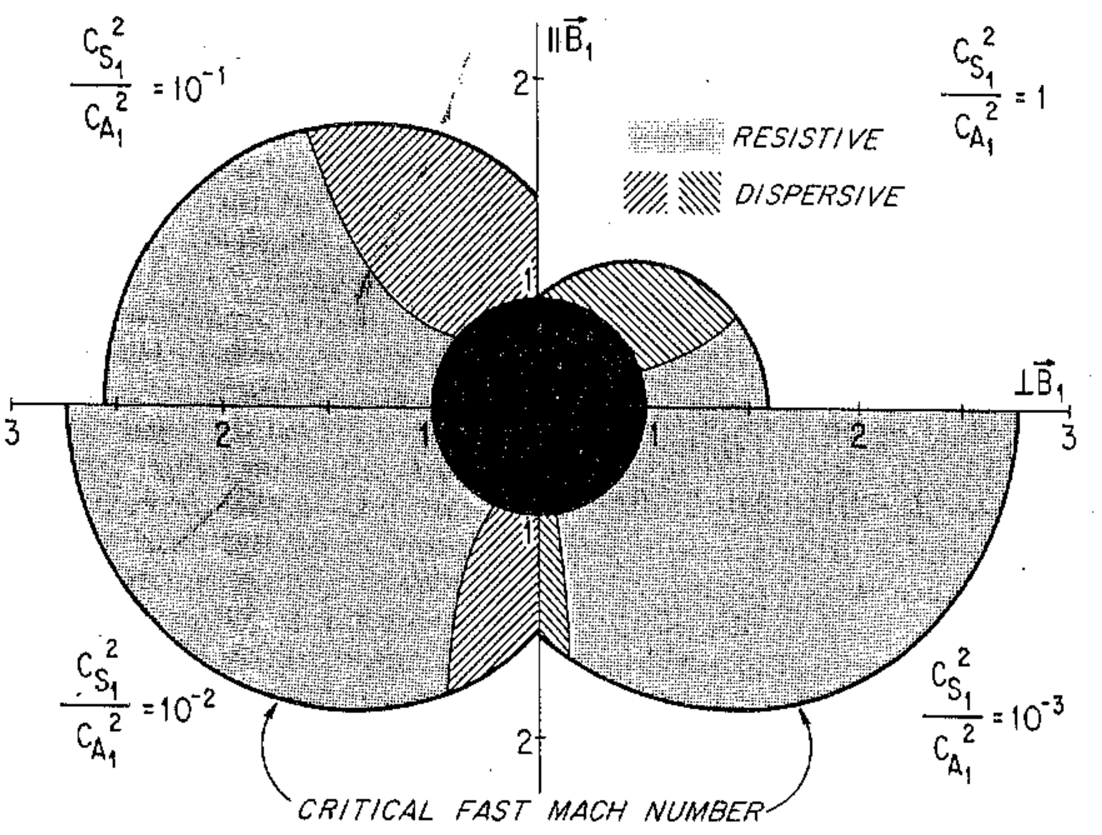


Greenstadt et al. [1975]

“Classical” sub-critical shocks ($\theta_{B,n}$ > 45)

The magnetic profile of both types of quasi-perpendicular low Mach number shock:

- Have a smooth transition across the ramp
- Do not exhibit an overshoot or any downstream oscillations
- Effects from ion reflection are expected to be minimal



Kennel [1985]

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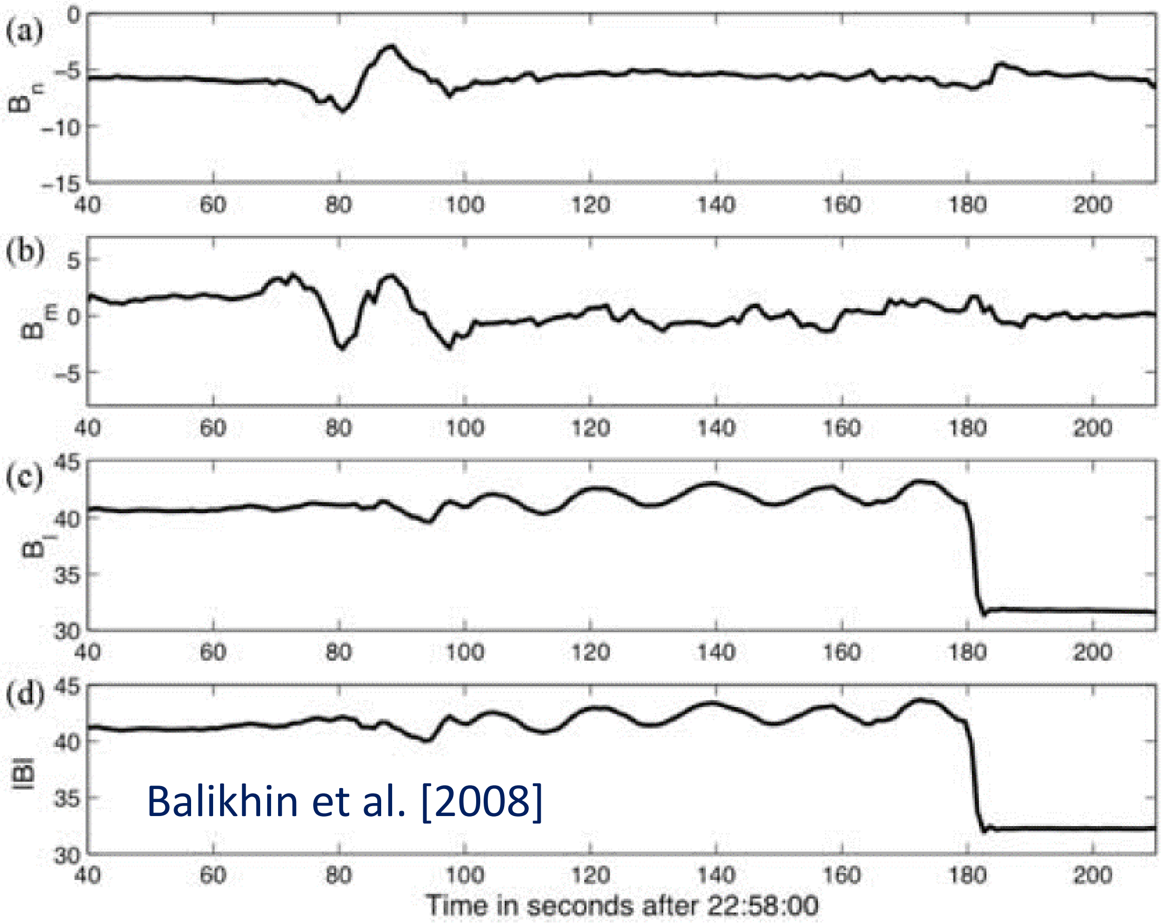
A new type of very-low Mach number shock



Balikhin et al. [2008]: A new structure of sub-critical shock observed at Venus:

- Quasi-perpendicular: $\theta_{B,n}$ = 70-80^o
- Very-low Mach number: increase across the ramp ~0.3|B_u|
- Magnetic over/undershoot and low frequency downstream oscillations
- Low frequency downstream oscillations polarised along the mean magnetic field.

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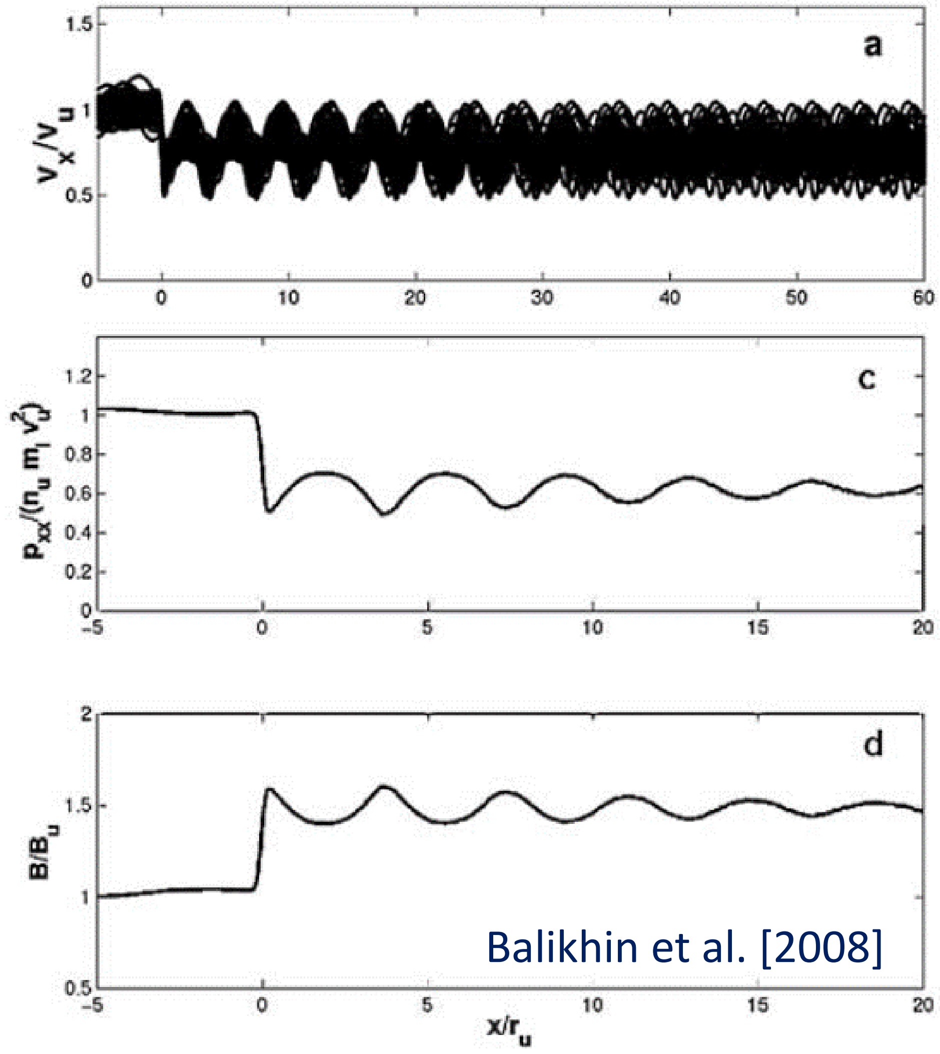
A new type of very-low Mach number shock – cont.

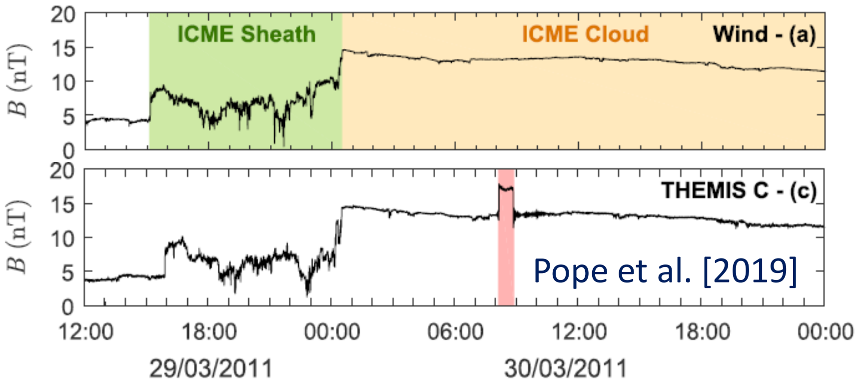


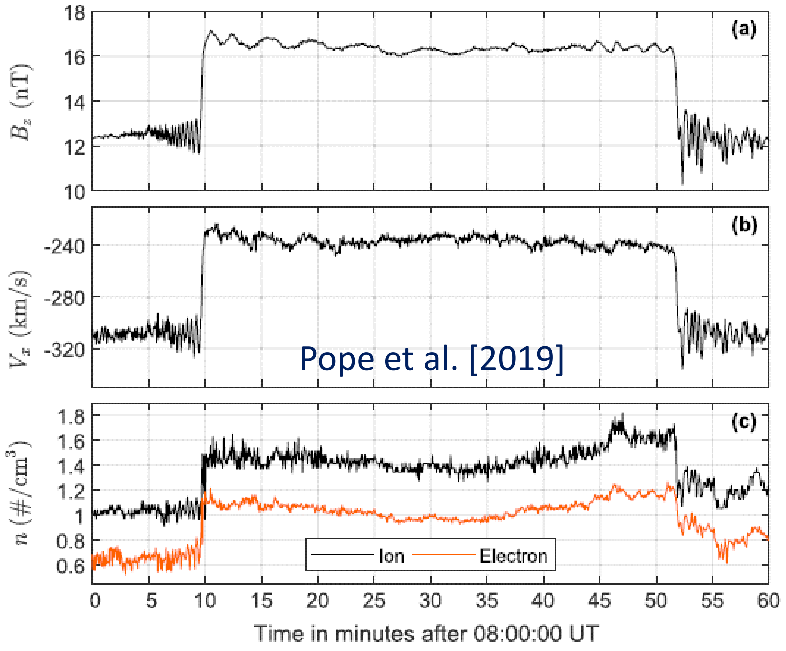
Balikhin et al. [2008]

Balikhin et al. [2008]: theory developed and effect shown in numerical analysis:

- Non-gyrotropic downstream ion distribution
- Magnetic pressure oscillations develop to cancel the ion pressure oscillations
- Gyrophase mixing cause oscillations to subside (due to ion temperature distribution)
- Can be observed when β is very small
- Suitable plasma data not available for verification

First observations at the Earth of kinematic” shocks





Shock observed in THEMIS C data (Pope et al. 2019):

- Very-low Mach number (M_A=1.2).
- Quasi-perpendicular ($\theta_{B,n}$ 69-71^o).
- Same profile in the magnetic field as Balikhin et al. [2008].
- Observed at SZA (solar zenith angle) 57^o and 57.7 R_E altitude.
- Abnormally high, but not unprecedented (e.g. Fairfield et al. [2001] 58 R_E at $\theta_{B,n}$ = 53°). Consistent with the Jeráb et al. [2005] model for the observed solar wind.
- Simultaneous magnetic field and plasma data allowed the non-gyrotropic downstream distribution to be observed and the out of phase oscillations in the plasma and magnetic pressures to be resolved for the first time, verifying the theory in Balikhin et al. [2008].

Data and Methodology

- The magnetic cloud phase of an ICME provide the conditions for such "kinematic" shocks to develop, e.g. very-low Mach number and low β (Pope et al. 2019).
- A survey of ICME magnetic clouds encountered by Venus during the entire Venus Express mission (previously compiled by Vech et al. 2015), has been conducted to identify the Venus bow shock crossings during these periods.
- Data from the magnetic field instrument MAG (Zhang et al. 2007) is presented here.
- In total 92 shock crossings were identified.
- These were usually part of a sequence of shocks crossings over a short time interval. This is due to small fluctuations in the very-low solar wind Mach number in the magnetic clouds, the primary driver for the Venus bow shock altitude (Russell et al., 1988), creating a shock that oscillates significantly across the spacecraft trajectory.

Data and Methodology – cont.

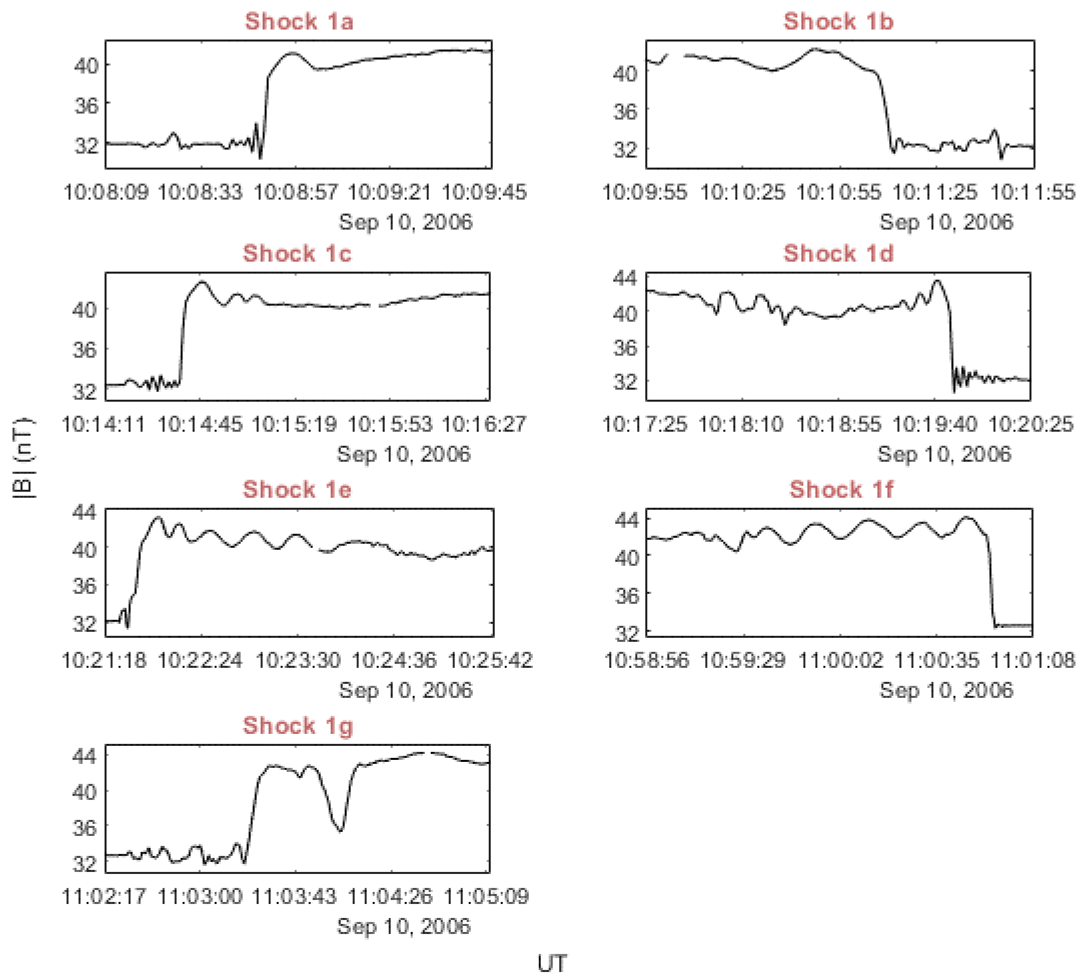
- Due to the reliance on single spacecraft measurements with low-sample rate, the shock normal for each of the shocks studied, is determined from the magnetic field data using both minimum variance analysis (MVA) and the coplanarity theorem (CP).

- The shock normal is used to determine the angle between the average upstream magnetic field and shock normal direction $\theta_{B,n}$

- The shock normal calculated from a model bow shock and observed solar zenith angle was not used due to the often abnormally high altitude of the observed shocks.

- The Alfvén Mach number for each shock was estimated from the magnetic field using $M_{A,B} \approx \sqrt{R\,(R+1)/2}$, where $R = B_d/B_u$ (ratio of downstream to upstream magnetic field magnitude). This is valid for cold perpendicular shocks (Gedalin et al. 2015). Pope et al. (2009) recently showed good agreement between this estimate and the directly calculated value $M_{A,B}$ for the “kinematic” shock observed at the Earth using THEMIS data.

Example 1: 10th September 2006



Shock	$\theta_{B,n_{mv}}$ (°)	$\theta_{B,n_{cp}}$ (°)	$M_{A,B}$	SZA (°)	A (R_V)	A_m (R_V)
1a	76	70	1.20	112	9.4	2.57
1b	79	79	1.20	113	9.4	2.58
1c	78	63	1.19	113	9.3	2.59
1d	84	83	1.19	113	9.3	2.61
1e	87	70	1.22	113	9.2	2.62
1f	82	80	1.23	116	8.6	2.80
1g	79	78	1.22	116	8.6	2.82

A sequence of seven shock crossings in under 1 hour:

- All quasi-perpendicular
- All had similar very-low Mach number and $\theta_{B,n}$
- Occurred in the night side flank
- Similar downstream magnetic field profiles
- This includes shocks previously studied by Balikhin et al. [2008]

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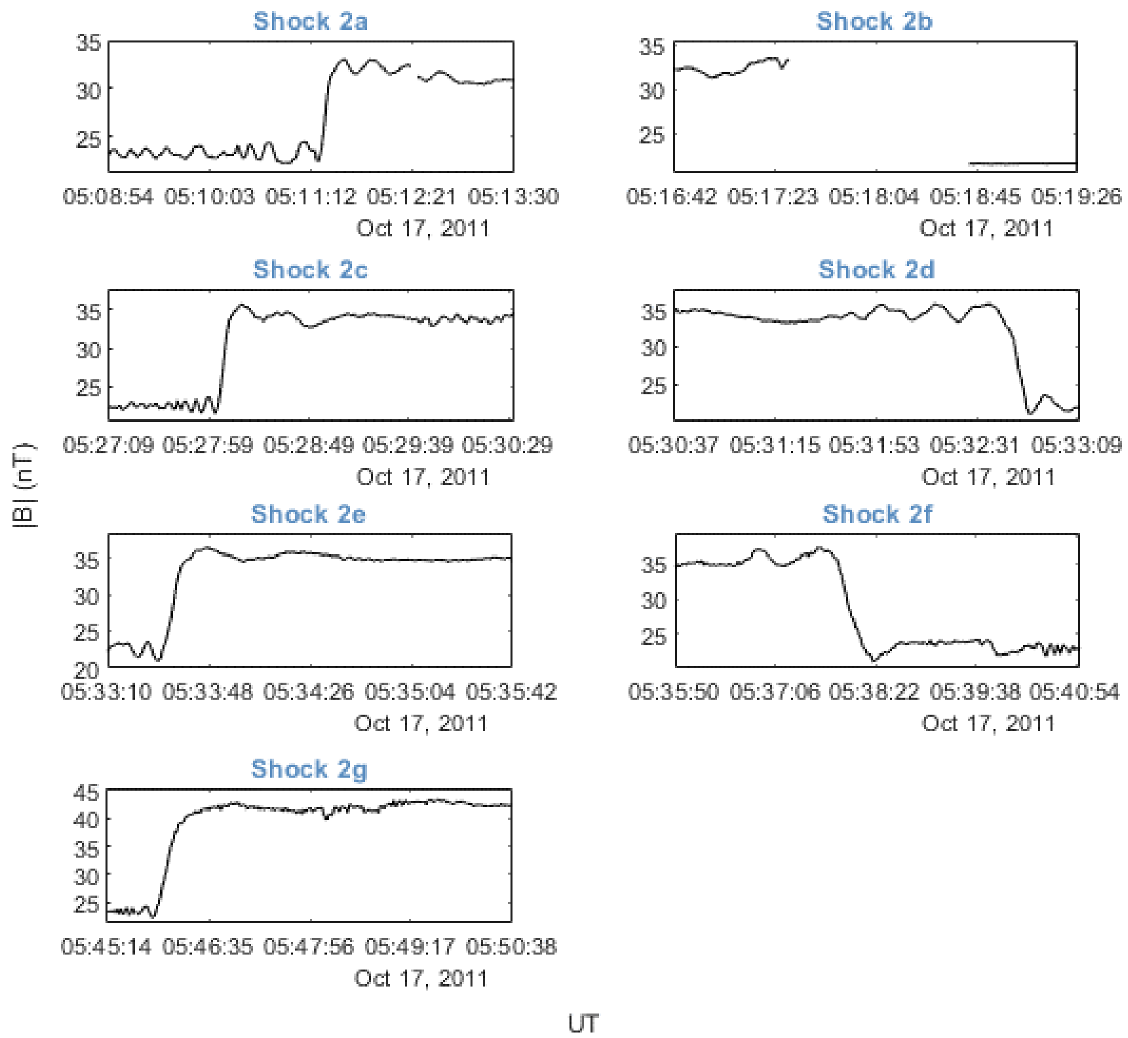
Example 2: 17th October 2011

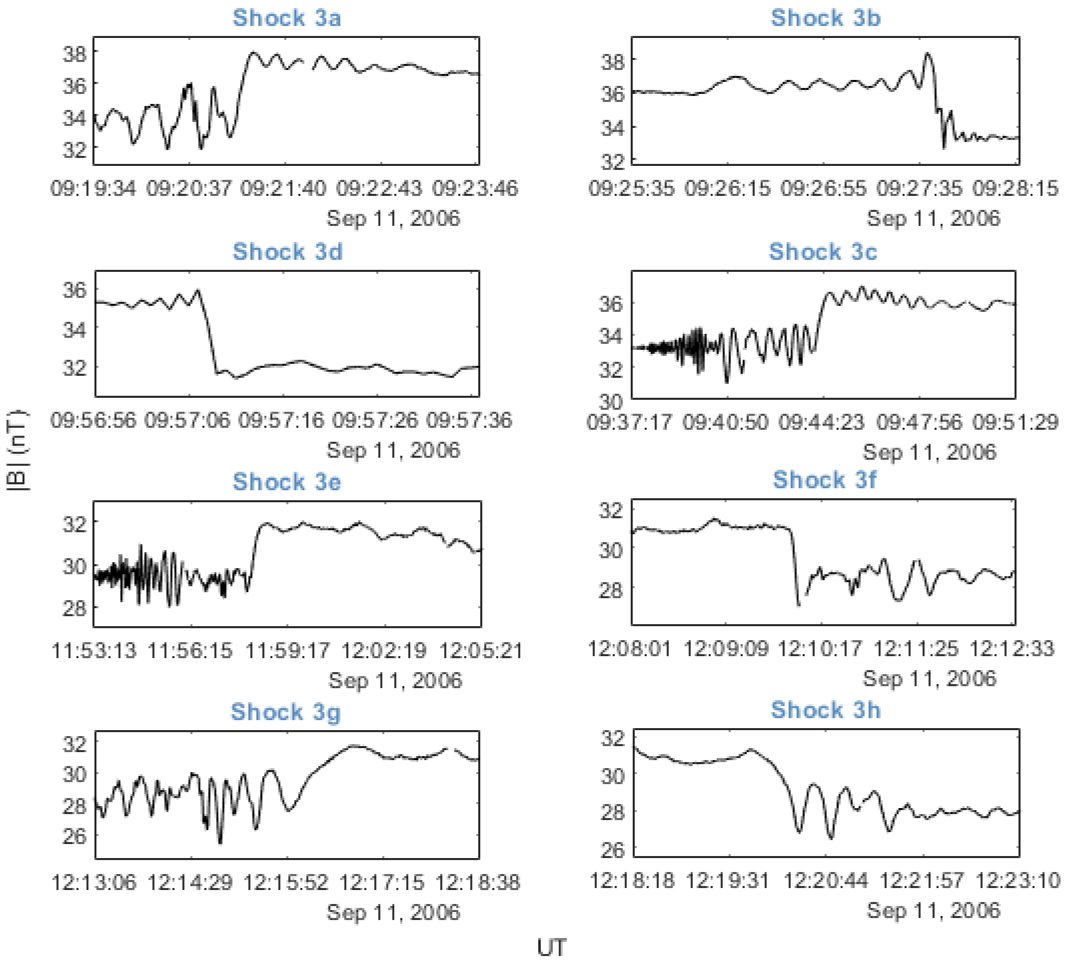


Shock	$\theta_{B,n_{mv}}$ (°)	$\theta_{B,n_{cp}}$ (°)	$M_{A,B}$	SZA (°)	A (R_V)	A_m (R_V)
2a	72	71	1.24	59	3.90	0.92
2b	ND	68	1.33	58	3.68	0.91
2c	66	65	1.37	55	3.29	0.88
2d	81	72	1.37	54	3.11	0.87
2e	67	68	1.40	54	3.08	0.87
2f	75	68	1.36	52	2.90	0.86
2g	74	69	1.56	50	2.57	0.84

A sequence of seven shock crossings in under 1 hour:

- All quasi-perpendicular
- The Mach number is very-low, but increases through the sequence
- Occurred in the dayside with SZA 50-59^{o}
- The magnitude of the downstream oscillations and the number of complete cycles reduces as the Mach number increases through the sequence.

Example 3: 11th September 2006

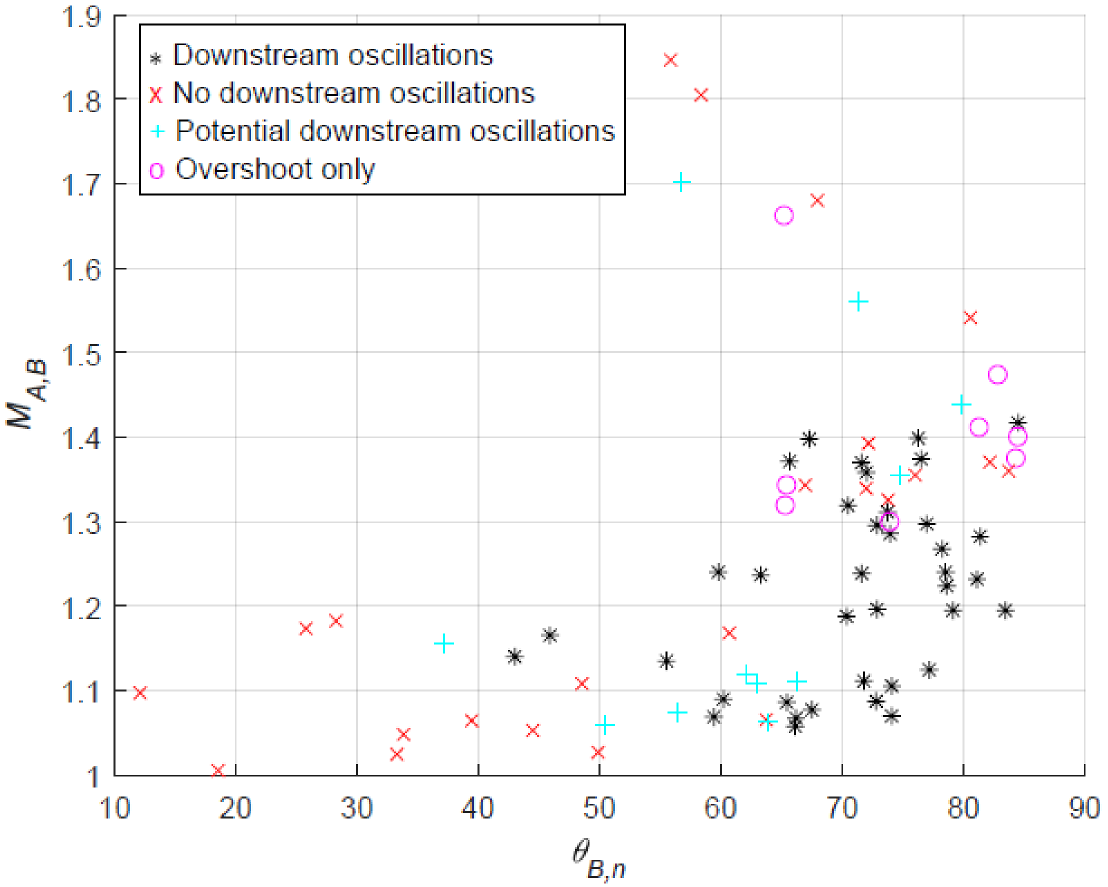


Shock	$\theta_{B,n_{mv}}$ (°)	$\theta_{B,n_{cp}}$ (°)	$M_{A,B}$	SZA (°)	A (R_V)	A_m (R_V)
3a	70	49	1.07	81	9.72	1.35
3b	85	63	1.07	82	9.80	1.35
3c	68	64	1.07	82	10.0	1.37
3d	77	53	1.09	83	10.2	1.38
3e	54	47	1.06	88	11.3	1.51
3f	74	54	1.07	89	11.3	1.52
3g	58	55	1.07	89	11.4	1.53
3h	64	64	1.06	89	11.4	1.53

A sequence of eight shock crossings over a 3 hour:

- All quasi-perpendicular, but $\theta_{B,n}$ varies from 54° to 85° (taken as the maximum value of the two vales estimated for each shock).
- All had similar very-low Mach number and towards the bottom end of the range of all shocks observed in the study.
- Occur just dayside of the terminator (SZA 81-89°)
- Downstream oscillations appear to be more likely to be present for shocks with larger $\theta_{B,n}$ (e.g. 3a, 3b and 3d) than those with smaller $\theta_{B,n}$ (e.g. 3e, 3g and 3h).

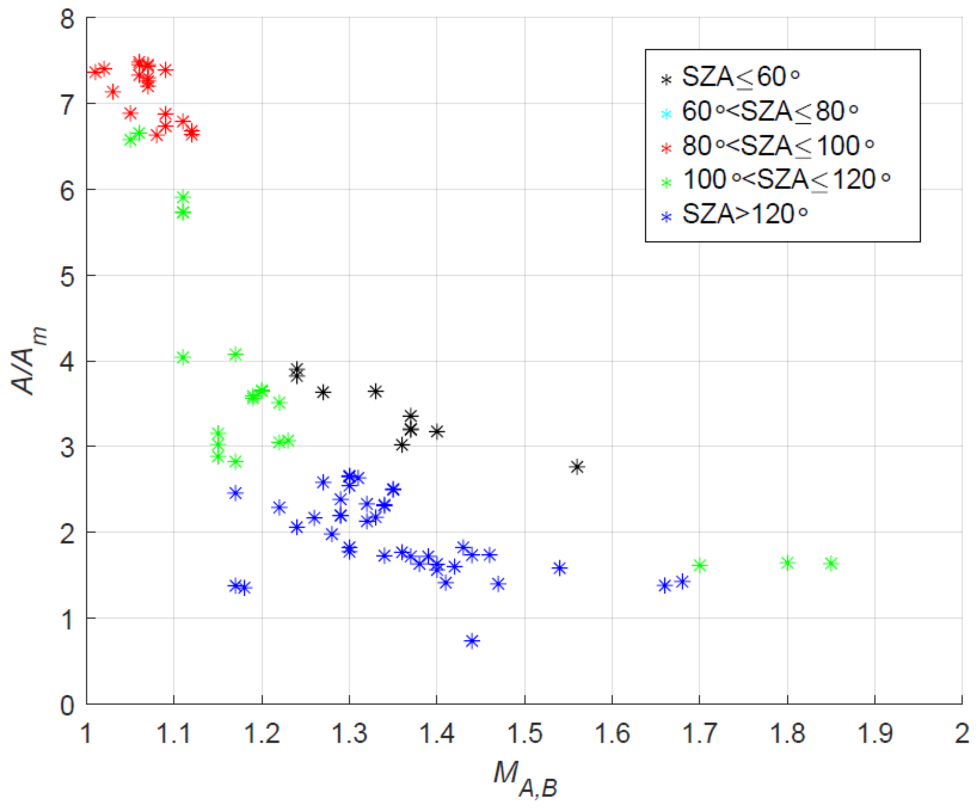
Effect of M_A and $\theta_{B,n}$ on Kinematic Relaxation



$\theta_{B,n}$ is the average of the CP and MVA derived values

- Most of the shocks with downstream oscillations are clustered in the region with $\theta_{B,n} > 50^o$ and $M_A < 1.4$.
- The transition to more quasi-parallel and higher Mach numbers is indicated by shocks with potentially some evidence of downstream oscillations or of an overshoot.
- The transition regions provide evidence that kinematic relaxation is only clearly observable for very-low Mach number quasi-perpendicular shocks.
- Evidence of just an overshoot is likely to be due to the formation of less than one period of the oscillations, i.e. the oscillations are quickly damped.

Spatial dependence of the observed shocks



- Very-low Mach number shocks identified in Venus Express data cover SZA's from 40º – 137º.
- Kinematic relaxation for quasi-perpendicular shock geometry is observed throughout this range of SZA. This indicates that when the solar wind conditions are suitable, any part of the bow shock is likely to form a structure in which kinematic relaxation is the dominant energy re-distribution mechanism.
- There is a tendency for the bow shock to move to a higher altitude as the Mach number falls, consistent with previous studies (Russell et al. 1988). The effect is more pronounced for $M_A < 1.6$, which is below the range previously studied. Above this value the altitude increase is less than a factor of two, but increases to greater than seven as $M_A = 1$ is approached.
- The SZA does not have a noticeable affect on the abnormal increase in shock altitude as the Mach number decreases.

Conclusion

KEY FINDING: Evidence of the downstream oscillations created by kinematic relaxation is only observable in shocks which are quasi-perpendicular and have very-low Mach number.

- During instances in which Venus interacts with the magnetic cloud phase of an ICME, 92 very low Mach number shock have been identified using Venus Express magnetic field data.
- Shocks with clear evidence of kinematic relaxation are clustered in a region with $\theta_{B,n} > 50^o$ and $M_A <$ 1.4. The transition from this region to more quasi-parallel and higher Mach numbers is indicated by the shocks with potentially some evidence of downstream oscillations or only an overshoot.
- Shock crossings which show kinematic relaxation are observed across a range of SZA from 40^o – 130^o. This indicates that it is likely that all locations of the Venus bow shock can form a structure in which kinematic relaxation is the dominant energy re-distribution mechanism.
- The altitude of the observed shocks are generally considerably higher than the Venus model bow shock and is correlated with a reduced M_A. This is consistent with previous results (Russell et al. 1988), but the increase is more pronounced for $M_A < 1.6$ which is below the range previously studied.

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Venus Express MAG data is available from ESA's Planetary Science Archive website. THEMIS and Wind data is available through the NASA Coordinated Data Analysis Web (CDAWeb) service.