# SHocks: structure, AcceleRation, dissiPation

## Work Package 5
## Database of shock crossings and software repository

## Deliverable D5.3
## Technical report on interplanetary (Artemis) section of the shock database

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on behalf of SHARP

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# Table of Contents

# 1 Summary

Artemis (THEMIS B and C) has been observing interplanetary shocks since 2008. A shock list produced by X. Zhou (the description by Zhou is appended in the end) covers the years 2008-2019 and contains about 400 shock crossings. We developed a database of these shocks which provides the basic shock parameters.

# 2 Detailed account or results

Interplanetary shocks form as a result of the interaction of solar wind streams of different velocity. Most interplanetary shocks are low- to moderate-Mach number shocks, while most bow shock crossings occur when the Mach number is high. The speed of the spacecraft relative to an interplanetary shock is typically much higher than the speed of the spacecraft relative to the Earth bow shock. All this means that observations of interplanetary shocks are different from the observations of the Earth bow shock, and that their treatment may be rather different. The first step in the shock analysis is determination of the normal. In the case of the Earth bow shock there exist models of the shock surface. A model shock normal is a quite good approximation of the global shock normal but not of a local normal. The latter may be quite different if the shock is rippled. Magnetic coplanarity and minimum variance provide the local normal, while mixed coplanarity, based on the magnetic field and plasma velocity, was shown to provide results close to the model shock normal for the Earth bow shock [Gedalin et al., 2021]. For interplanetary shocks no model normal exists, so that the natural choice is to use the mixed coplanarity. Besides magnetic field, this method requires good knowledge of the upstream and downstream densities and the upstream and downstream velocity vectors. Artemis measures these parameters for ions and electrons separately. The scientific payload of THEMIS is not quite appropriate for the solar wind plasma measurements. The electron moments are expected to be more reliable than the ion moments. We checked reliability of the electron measurements by comparison with the Wind measurements for several shocks. The Artemis and Wind electron measurements were quite consistent. We have not checked this consistency for all $\sim 400$ shocks though. We used separately ion moments and electron moments for determination of the shock normal, shock speed, Alfvén speed, Alfvén Mach number. We have not calculated the fast magnetosonic Mach number since this requires reliable knowledge of the upstream temperatures. The procedure was as follows:

a) for each shock the data was downloaded using Spedas software with IDL;

b) we used the low-resolution magnetic field data in the spacecraft coordinates (FGM_fgs_dsl);

c) we used the online ion and electron density and velocity vector in the spacecraft coordinates;

d) for each shock the magnetic field and densities were plotted in a single figure and the upstream and downstream region were selected visually.

The shock parameters were calculated in the usual way:

$$\Delta \boldsymbol{B} = \boldsymbol{B}_d - \boldsymbol{B}_u \tag{1}$$

$$\Delta \boldsymbol{V} = \boldsymbol{V}_d - \boldsymbol{V}_u \tag{2}$$

$$\hat{l} = \frac{\Delta \boldsymbol{B}}{|\Delta \boldsymbol{B}|} \tag{3}$$

$$\hat{m} = \frac{\hat{l} \times \Delta \boldsymbol{V}}{|\Delta \boldsymbol{V}|} \tag{4}$$

$$\hat{n} = \hat{m} \times \hat{l} \tag{5}$$

$$V_{sh} = \frac{(n_d \boldsymbol{V}_d - n_u \boldsymbol{V}_u) \cdot \hat{n}}{n_d - n_u} \tag{6}$$

$$V_u = \frac{(\boldsymbol{V}_d - \boldsymbol{V}_u) \cdot \hat{n}}{1 - n_u/n_d} \tag{7}$$

$$v_A = 21.8 \frac{\sqrt{|\boldsymbol{B}_u|}}{n_u} \tag{8}$$

$$M_A = \frac{V_u}{v_A} \tag{9}$$

Figure 1 illustrates the procedure and the problems with the particle data.

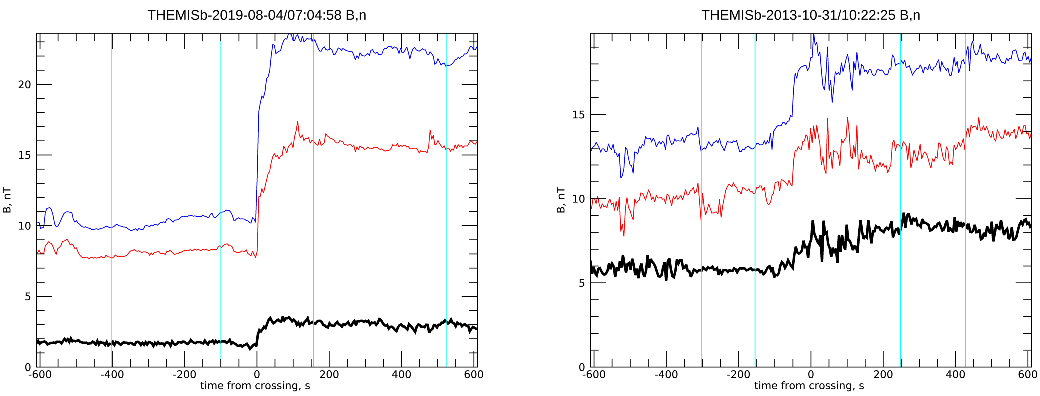


Figure 1: Magnetic field magnitude (nT, black curve), ion density (cm$^{-3}$, red curve), and electron density (cm$^{-3}$, blue curve). The vertical cyan lines denote upstream and downstream.

The following parameters were saved for each shock:
a) crossing times in human readable form;
b) probe: Themis B or C;
c) chosen upstream and downstream regions in sec relative to the crossing time;
d) upstream and downstream magnetic field vectors and magnitudes;
e) upstream and downstream ion velocities;
f) upstream and downstream electron velocities;
g) ion upstream and downstream densities;
h) electron upstream and downstream densities;
i) maximum magnetic field magnitude between upstream and downstream;
j) normal calculated from mixed coplanarity (magnetic field and ion velocity);

k) Alfvénic Mach number and shock angle from mixed coplanarity (magnetic field and ion velocity);
l) normal calculated from mixed coplanarity (magnetic field and electron velocity);
m) Alfvénic Mach number and shock angle from mixed coplanarity (magnetic field and electron velocity).

# 3 Statistical analysis

Some statistical analysis is presented here in a number of figures. Explanations are given in the figure captions. We exclude all points with $n_d/n_u > 4$ or $B_d/B_u > 4$. Larger density or magnetic field ratios are not allowed by the Rankine-Hugoniot relations. Such ratios mean that either the measurements are not reliable or the upstream and downstream regions are chosen incorrectly. It is possible also that one of both regions are so strongly disturbed that the uniform states are not achieved. In the latter case neither Rankine-Hugoniot relations nor coplanarity conditions are applicable. Among overall 410 shocks for 387 both compression ratios are within the limit imposed by the Rankine-Hugoniot relations. This is better than for the Earth bow shock observations and is apparently related to the better identification of the downstream region for Artemis shocks, probably due to the generally lower Mach numbers or broader downstream region (for interplanetary shocks it is not limited by the distance from the shock to the magnetopause).

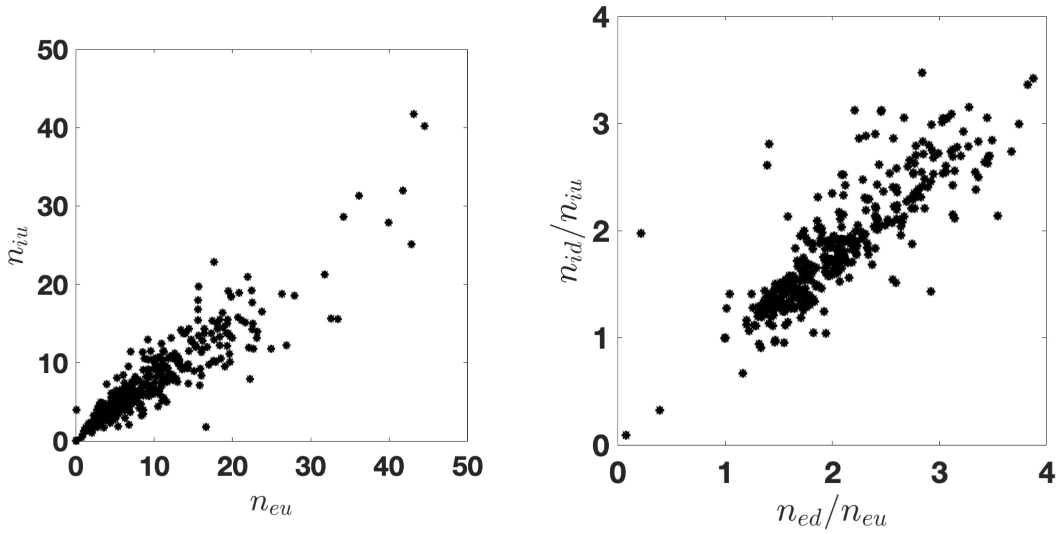


Figure 2: Left: the upstream electron density $n_{eu}$ vs the upstream ion density $n_{iu}$. The agreement for $n < 25$ cm$^{-3}$ seems better than expected. Right: The electron density ratio $n_{ed}/n_{eu}$ vs the ion density ratio $n_{id}/n_{iu}$. There is certain overall agreement between the ion and electron density measurements.

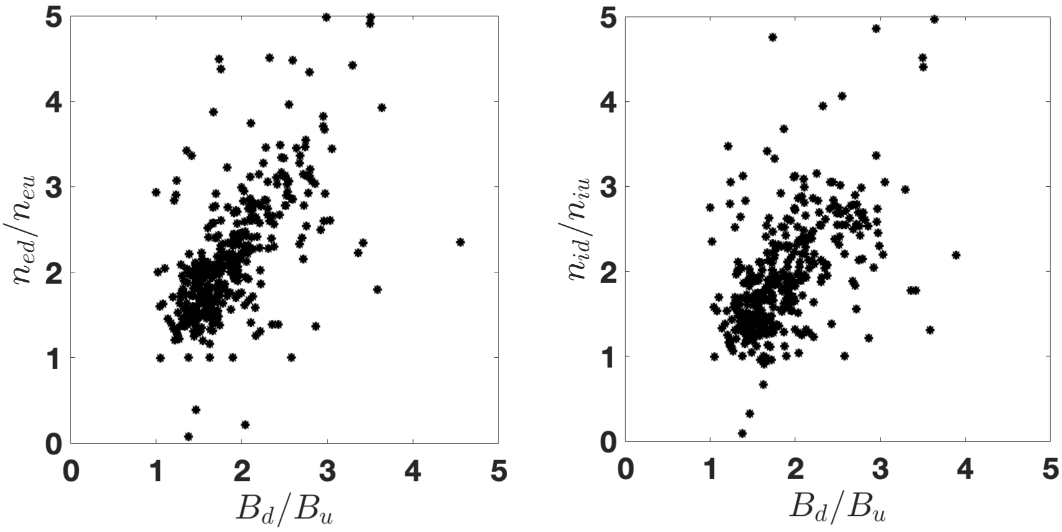


Figure 3: Left: the magnetic compression $B_d/B_u$ vs the electron density ratio $n_{ed}/n_{eu}$. Right: same for ions.

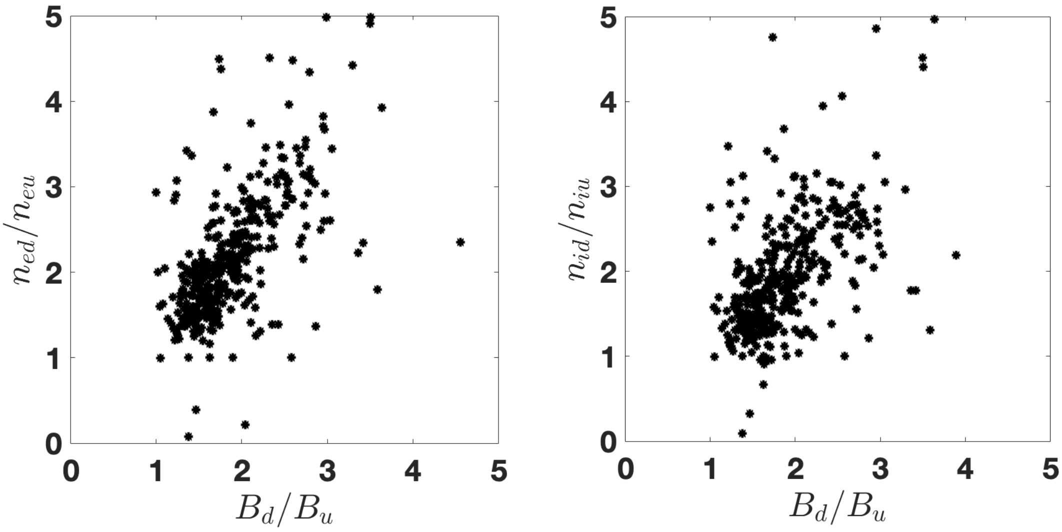


Figure 4: Left: the magnetic compression $B_d/B_u$ vs the electron density ratio $n_{ed}/n_{eu}$. Right: same for ions.

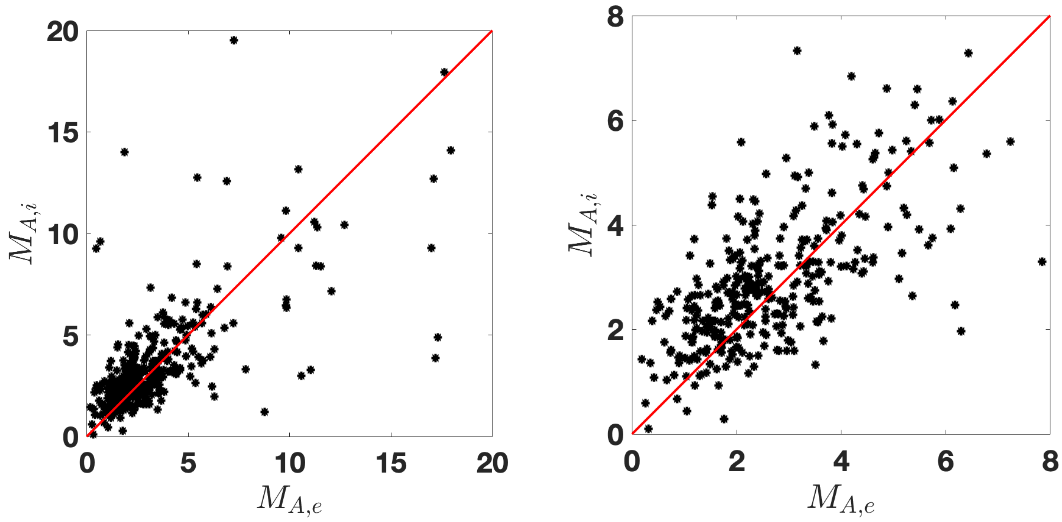


Figure 5: Left: comparison of the Mach numbers calculated using electron moments (black) and ion moments (red). Right: same for $M_A < 8$. The highest found Mach numbers $> 20$ are not reliable. For $M_A < 20$ we found that $\langle M_A \rangle \approx 3$ and $\langle (M_A - \langle M_A \rangle)^2 \rangle \approx 4.5$ in both cases.

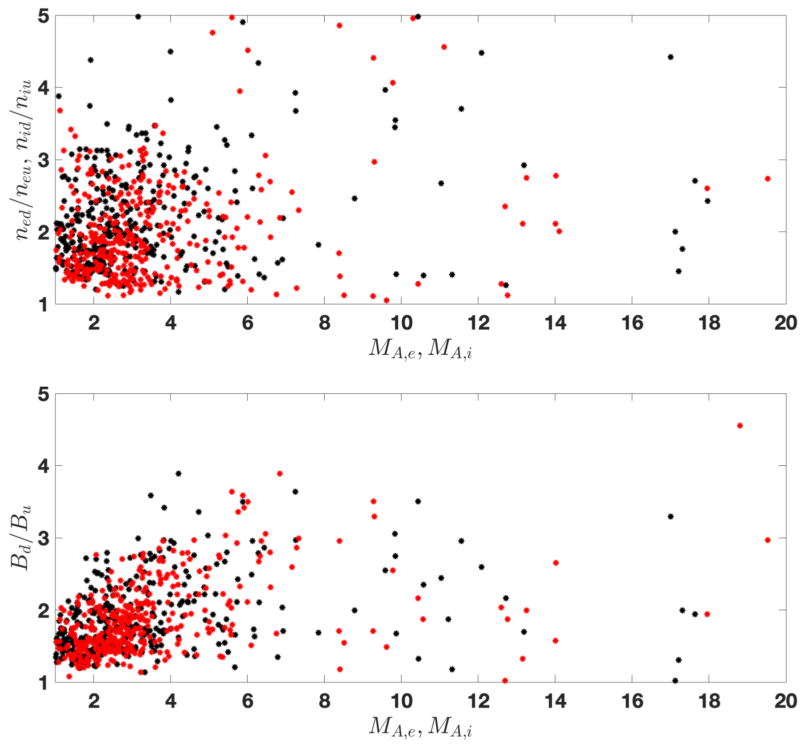


Figure 6: Top: Mach numbers calculated using electron moments (black) and ion moments (red) vs corresponding density ratios. Bottom: Mach numbers calculated using electron moments (black) and ion moments (red) vs magnetic compression.,

# 4 Description of the shock list

**ARTEMIS Interplanetary-Shock List**

- Interplanetary shocks in the list are observed by the two ARTEMIS spacecraft, THB and THC, when they are in the solar wind and/or in the magnetosheath. Cases when the spacecraft is in the lunar wake are also included.
- The listed shocks are also confirmed by observations from Wind, ACE, SOHO and the ground magnetograms.
- In the column of Probe, THB means a fast forward shock detected by THB click which a THB summary plot around the shock opens up through the link to the THEMIS website; THB(FR) presents a fast reverse shock observed by THB; THB(sh) presents an fast forward shock observed by THB in the magnetosheath; THB(wk) is for the shock effect observed by THB in the lunar wake.
- The shock time in UT is identified using FGM data.
- Spacecraft positions are the position when a shock is recorded and are given in GSE and SSE in Re and Rm, respectively, using Re = 6374 km and Rm = 1737 km. By clicking the X component in GSE, an orbit plot in GSE opens up through the link to the THEMIS website, on which an additional click leads to the orbit plot in SSE.
- In the column of Data Mode, F is for fast survey during which fgm_fgl is available with 0.25-sec resolution; S for slow survey and only fgm_fgs is available with 4-sec resolution; F,PB,WB presents fast survey with particle and wave burst mode during which fgm_fgh is available with a resolution of 128 samples per second.
- Shock parameters, such as the shock normal, ThetaBn, shock speed, shock Mach number, and shock criticality are given in the table in Zhou et al. [2020]. Our analyses use the method discussed in Zhou and Smith [2015].

Zhou, X.-Y. and E.J. Smith, Super-Criticality of ICME and CIR Shocks, *J. Geophys. Res. Space Physics, 120,* doi:10.1002/2014JA020700, 2015.

Zhou, X.-Y., M. Gedalin, C. T. Russell, V. Angelopoulos, A. Drozdov, Criticality of Low-Mach-Number Interplanetary Shocks, submitted *to Frontiers in Physics*, 2020

Figure 7: Description of the Artemis observed interplanetary shock list compiled by X. Zhou.

# 5 References

Michael Gedalin, Christopher T. Russell, and Andrew P. Dimmock. Shock Mach Number Estimates Using Incomplete Measurements. *J. Geophys. Res*, 126(10): e2021JA029519, 2021. ISSN 2169-9402. doi: 10.1029/2021JA029519.