Collisionless Physics and Hydrodynamics of Earth's Bow Shock

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Abstract

Earth's bow shock is a standing shock wave where the Earth's magnetosphere meets the solar wind, a collisionless, super-sonic plasma coming from the sun. At the bow shock, solar wind plasma is heated, compressed and energized before it interacts with the magnetosphere. The physics and predictions for the bow shock have been primarily considered using a fluid, magneto-hydrodynamic (or MHD) description, despite the fact that the conditions of the bow shock violate the basic assumptions of MHD. Motivated by recent advances in kinetic plasma theory, we use high cadence, multi-point measurements of the magnetic fields and plasma quantities made by NASA's Magnetospheric Multiscale (MMS) satellites at Earth's bow shock to test if the predictions of MHD are applicable for this system. We find that the compression ratio measured by MMS has little to no correlation with the MHD predictions and we investigate different possible explanations for this deviation. These findings have important implications for the interaction of solar wind and the magnetosphere, as well as for space weather modeling more generally.

Introduction and Methods

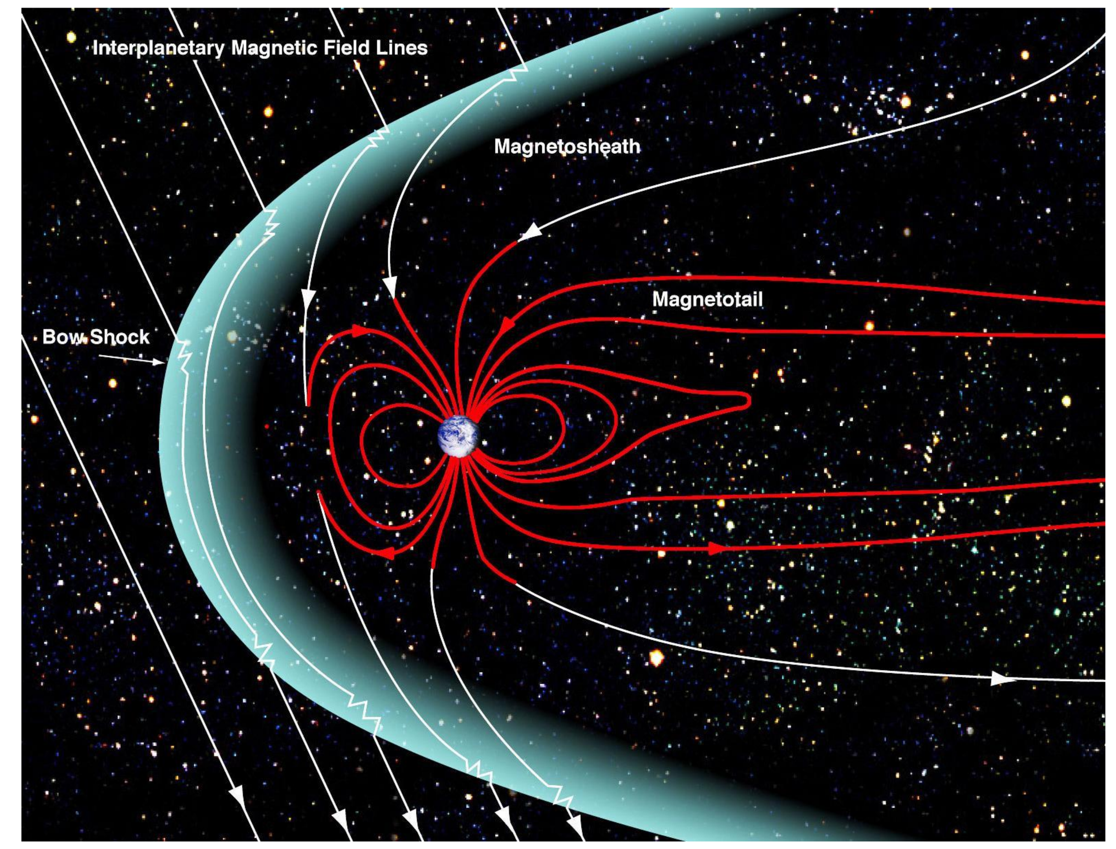
Shocks are disturbances that move faster than the local speed of sound in the medium and cause a change in density. When shocks are collisionless, the mean free path, the distance a particle will go before a collision, is much larger than the transition from pre-shock to post-shock. Bow shock is a collisionless shock that occurs when the magnetosphere of an object interacts with flowing plasma. When plasma interacts with a shock, it can energize particles.

Shock waves have upstream and downstream components. The upstream is the incoming particles, before they have reacted to the shock, and typically have faster velocity and lower density. The downstream are the particles after the shock, and typically have slower velocity and higher density.

Traditionally, the compression ratio is thought of to at most four, depending on the magnetosonic Mach number. However, the model is based on MHD which assumes that collisions are frequent, while Earth's bow shock is collisionless.

We use data from the four Magnetospheric Multiscale (MMS) spacecrafts. Ion moments and distribution functions are from the Fast Plasma Investigation Dual Ion Spectrometer (FPI-DIS), and electron moments and distribution functions are from the Fast Plasma Investigation Dual Electron Spectrometer (FPI-DES). Magnetic field data are from the FluxGate Magnetometer (FGM) instrument, which provides magnetic field vector measurements. All upstream solar-wind parameters are from a set of spacecraft positioned upstream of MMS at the first Lagrange point. The solar-wind data are time shifted to the bow shock and provided by the OMNI database with a time resolution of one minute.

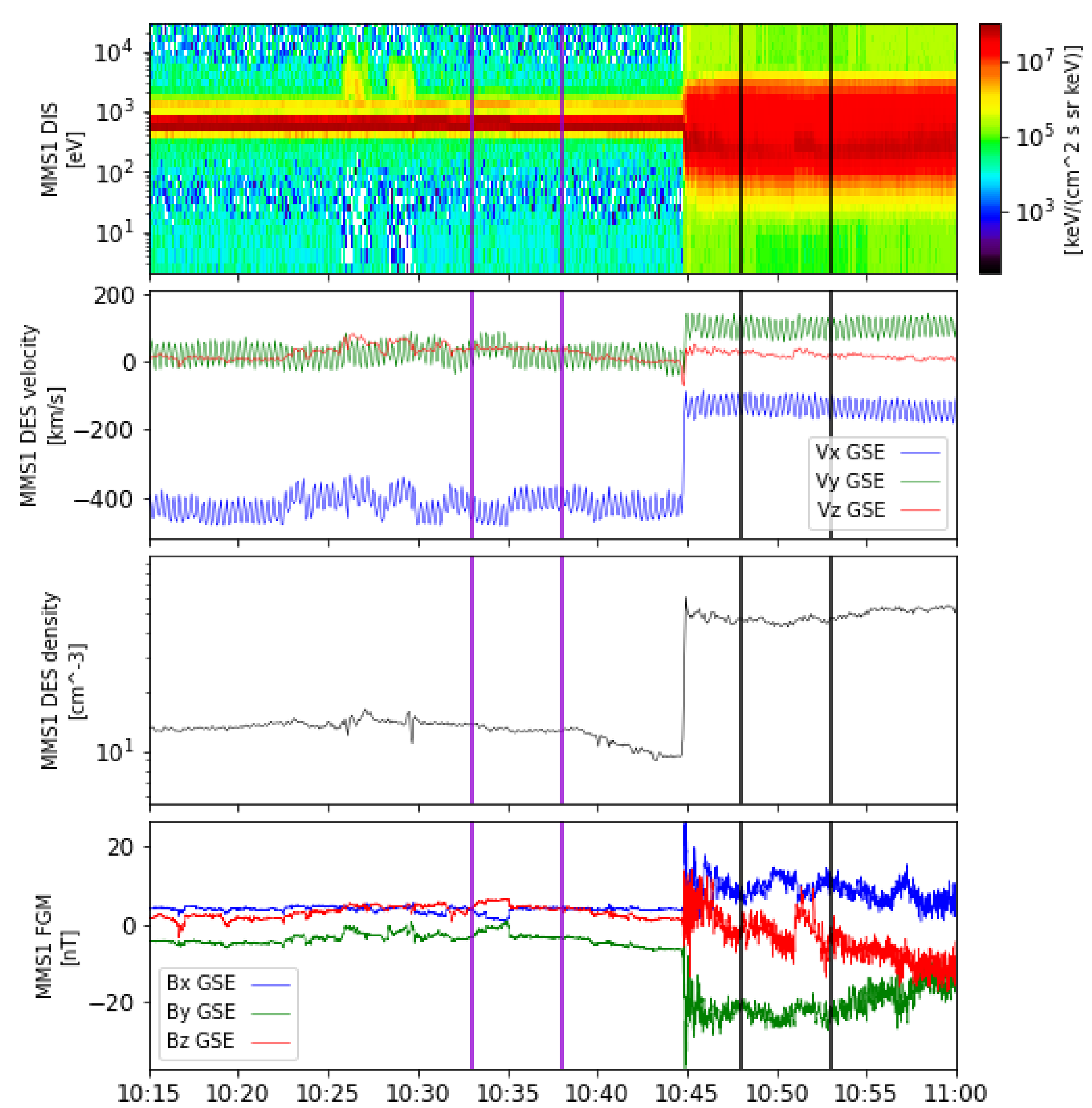
We took multiple shock crossings and calculated the compression ratio using electron number density from the upstream and downstream.



NASA depiction of Earth's magnetosphere and bow shock

$$r = \frac{(\Gamma+1)M^2}{2+(\Gamma-1)M^2}$$

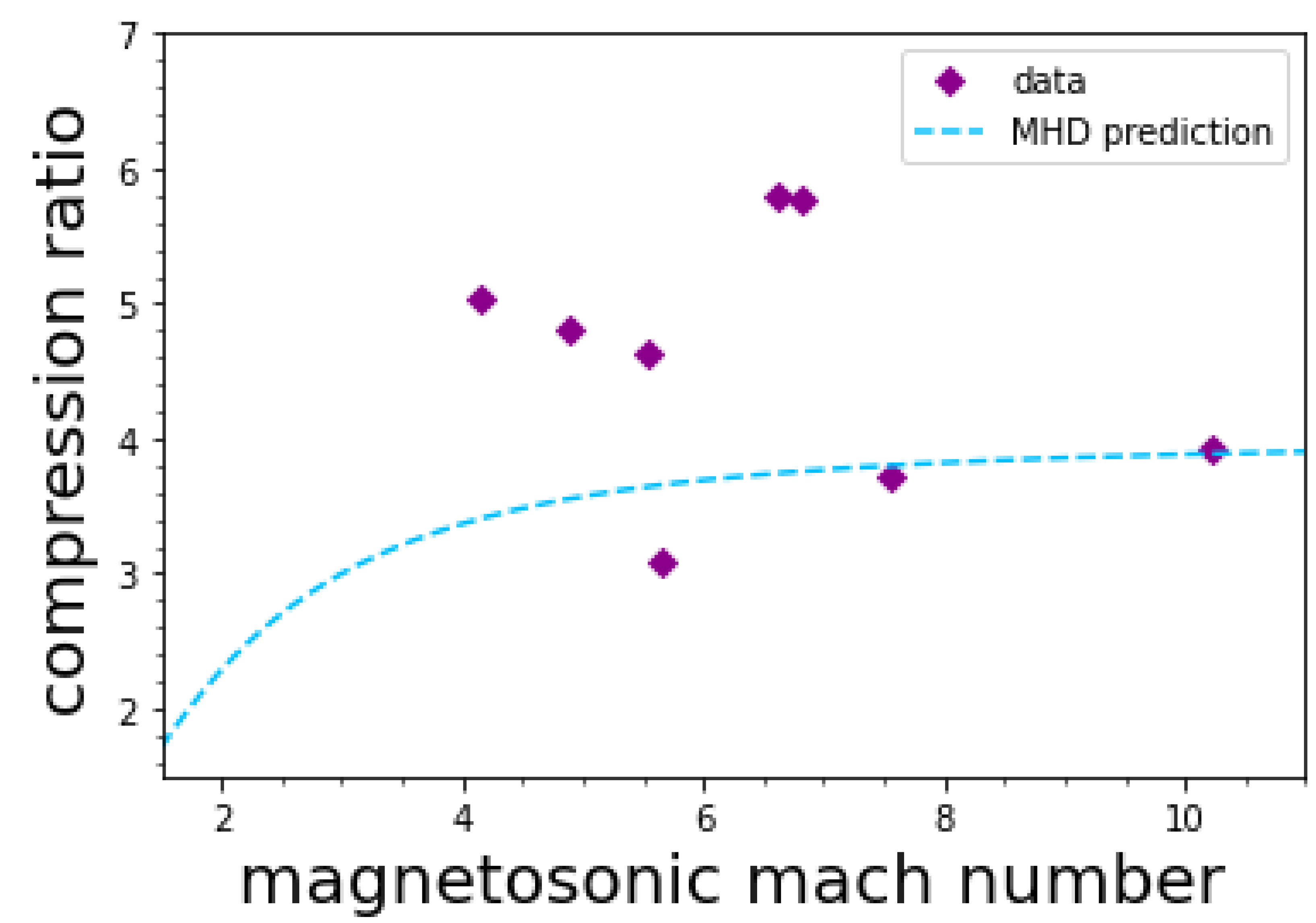
MHD prediction for compression ratio



Shock Crossing at around 10:45, the purple bars show where we took downstream data, the black bars show where we took the upstream. Graphs from top to bottom: energy (eV), electron velocity (km/s), electron density (cm^-3), and magnetic field(nT)

Results and Discussion

The relationship between the compression ratio and the supersonic Mach number does not match traditional MHD predictions. However, because of so many factors, it is still unclear if MHD is an accurate prediction for the bow shock.



Conclusions

In this work, we studied a collection of shock crossings by the MMS spacecraft, and it is unclear if MHD is a good depiction for the bow shock. It is important to note that there are limitations to what can be done with MMS for studying the bow shock. These reasons may include a time variation of the shock, and issues with MMS. Another potential reason could be non-local issues, the fact that the OMNI data may not be reporting the same plasma that MMS is. Finally, MHD is the traditional model for collisional shocks, while bow shock is collisionless.

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References

1. D. N. Baker et al. 2016, Magnetospheric Multiscale Instrument Suite Operations and Data System.
2. A. R. Bell 2004, Turbulent amplification of magnetic field and diffusive shock acceleration of cosmic rays.
3. C. Haggerty and D. Caprioli 2020, Kinetic simulations of cosmic-ray-modified shocks.
4. A. Johlander et al. 2021, ion acceleration efficiency at the earth's bow shock: Observations and simulation results.
5. J. H. King and N. E. Papitashvili 2005, Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data.
6. G. F. Krymskii 1977, A regular mechanism for the acceleration of charged particles on the front of a shock wave
7. C. Pollock et al. 2016, Fast Plasma Investigation for Magnetospheric Multiscale
8. C. T. Russell et al. 2016, The Magnetospheric Multiscale Magnetometers