

Earth's bow shock dynamics and structure scales based on MMS multi-spacecraft data

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Abstract. Space plasmas studies on bow shock dynamics and structure scales continue to attract intense theoretical and experimental investigations. The Earth's bow shock is the closest shock accessible to scientists through various satellite missions. These missions have enabled investigations on different physical phenomena associated with solar-terrestrial interaction. Access to the interplanetary medium through satellites has provided access to valuable spatial and temporal data on the Earth bow shock, and has furthered understanding on certain aspects of shock physics that were inaccessible until now. The main objective of this study is to quantify the dynamics and structure scales of the Earth's bow shock using data obtained by the MMS multi-spacecraft during shock crossing.

1. Introduction

The initial investigations on shock motion date back to the 1960's [2, 3]. Single satellite observations have estimated shock speeds of ~ 10 km/s on an average. Shock motion may result from several disturbances in the solar wind ram pressure. Völk and Auer's [7] work forms the sole exhaustive study, although restricted to the nose region, of the impact of the solar wind conditions on variations in the shock motion. Before multi-spacecraft missions such as Cluster and MMS, all shock motion measurements were performed on data collected by a single or dual spacecraft. Meziane et al. [1] analyzed the data from 133 shock crossings collected by Cluster. The study found that the shock velocity distribution could be satisfactorily described by a zero-mean Gaussian for speeds less than ~ 80 km/s as shown in Figure (2). This implies that the shock move under solar wind ram pressure, earthward and sunward, fluctuates randomly. In their study, Meziane et al. [1] showed that the distribution of the shock normal for 133 crossings derived from timing analysis [4] indicated that the shock motion is along the $x - GPE$ [6]. Consequently, the shock move inward (outward) along the Sun-Earth direction is shown in Figure (1). Alrefay [6] showed that the propagation of Alfvén waves interacting with the shock induced shock speed of the order of 10 km/s or less on an average. Based on the systematic inward-outward shock motion, Meziane et al. and Alrefay [5, 6] constructed the probability function (PDF) for the shock velocity near the nose region and compared it with the distribution of the ram pressure fluctuations and derivative of the ram with respect to time fluctuations as shown in Figure (3, 4). The ram pressure temporal changes provided shock velocity values that agreed with the observations [6]. Because the technique of measurement comprises determination of time delays as explained in the next section, a fundamental assumption stipulates that the shock front is quasi-stable during successive measurements. Depending on the involved time



scales, the validity of this assumption may be violated given the shock reformation process. Quasi-perpendicular supercritical shocks usually appear as a sharp transition. However, high-precision time magnetic field measurements indicate that the shock transition layer presents short time variations of the different structures making up the shock. This raises serious difficulties in the analysis of shock motion as derived from successive shock crossings. In this study, we focus on the shock dynamics and shock structure scales by using multipoint measurements provided by the MMS quartet, which comprise high-precision time magnetic field measurements. This allows for an in-depth investigation on the effects of a shock's ramp scales and obtained shock motions. We provide two examples of shock crossings observed by the MMS spacecraft and its dynamics.

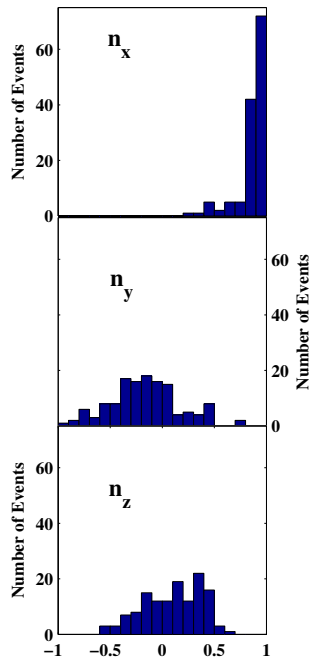


Figure 1. Histogram for the direction of shock motion along the three Cartesian coordinates

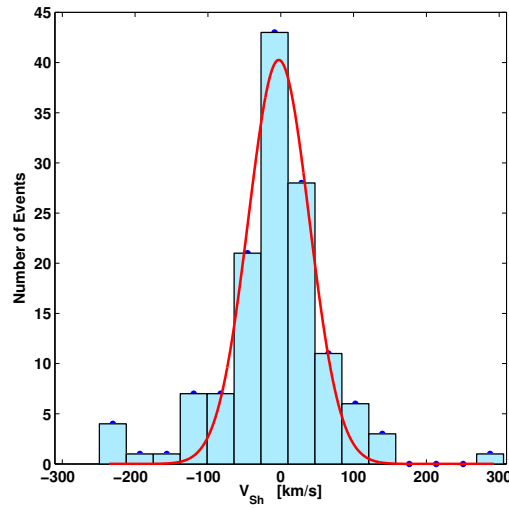


Figure 2. Shock velocity distribution

2. MMS Data analysis (Timing Analysis Method)

The MMS Multi-Spacecraft provides full three-dimensional shock velocities, shock normals, and shock structure scales. The time delay between successive shock crossings is determined by using the timing analysis and cross-correlation between the MMS spacecraft signals assuming that the bow shock is planar and moving with constant velocity at the scale of the MMS quartet during the time of interest [8]. If the same bow shock passes the MMS quartet, the relative position and successive time delay can be used to construct the bow shock normal $\hat{n}$ and velocity $\vec{V}_{sh}$ from the solution of the following system [4].

$$\begin{pmatrix} \vec{r}_{13} \\ \vec{r}_{23} \\ \vec{r}_{43} \end{pmatrix} \cdot \frac{1}{V} \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix} = \begin{pmatrix} t_{13} \\ t_{23} \\ t_{43} \end{pmatrix} \quad (1)$$

In equation (1), the (n_x, n_y, n_z) are the components of the normal vector $\hat{n}$, and V_{sh} is the shock speed. During the time delay t_{13} , the bow shock plane moves by a distance of $V(t_1 - t_3)$ along

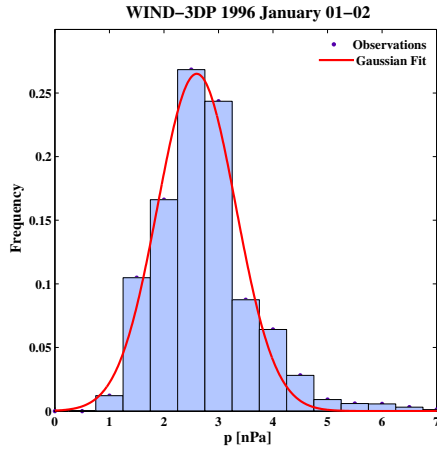


Figure 3. Solar wind ram pressure distribution

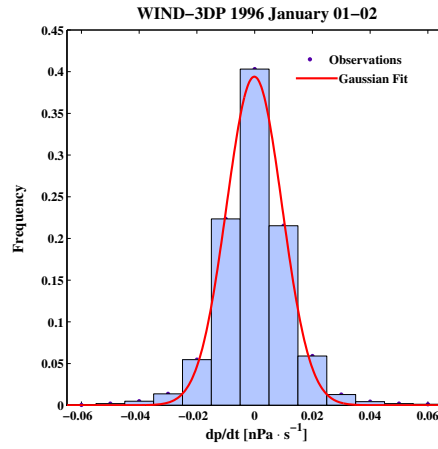


Figure 4. Solar wind dp/dt distribution

the normal between MMS3 and MMS1, which is equal to the projection of the inter-spacecraft separation $\vec{r}_1 - \vec{r}_3$ onto the normal [10]. This method is used here for determining the normal and velocity along the normal of the Earth's bow shock. The timing method assumes that the bow shock structure is planar over the MMS spacecraft configuration scale [8]. To improve the determination of the time delay between two successive shock crossings, high frequency-IMF fluctuations, when present, are removed or suppressed using appropriate techniques such as low band-pass filtering or moving averages as shown in Figure (5). For this crossing, a time resolution of 16 Hz is used for the interplanetary magnetic field data, which is good enough when the spatial ramp thickness is not too small. However, some studies show that the thickness of the shock ramp structure; the time domain is translated into distance assuming that the shock structure moves with a constant velocity obtained by timing analysis of the interplanetary magnetic field. For this shock crossing of the MMS spacecraft, the results of timing analysis as well as solar wind condition and shock geometry are given in Table (1)

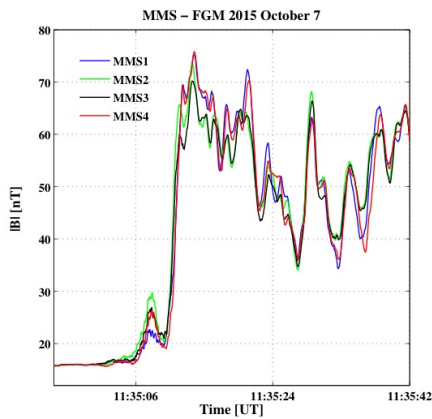


Figure 5. An Example of a bow shock crossing where moving averages are used on the time series of IMF measurements.

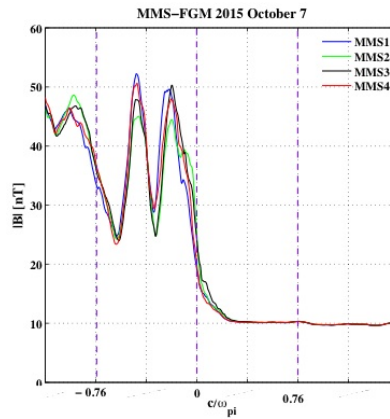


Figure 6. An Example of a bow shock crossing where time is converted to distance and normalized to upstream proton inertia length.

Table 1. Two Shocks Parameters (2015 Oct 07)

Parameters	Unit		
Crossing Time	hh:mm:ss	11:35:10	11:37:26
$\hat{n}$	-	(0.895 0.447 0.0)	(0.873 -0.486 -0.004)
V_{sh}	km/s	+3	-4
θ_{Bn}	deg	79°	79°
M_A	-	6.30	10.60
M_s	-	6.70	5.60
β	-	1.20	1.70
c/ω_{pi}	km	41	37
Standoff distance	R_E	10.40	11.50

3. Conclusions

This paper described preliminary investigations on the Earth's bow shock crossing using data from MMS multi-spacecraft. The dynamics and shock structure scales were obtained by applied timing analysis. Several shock crossings were identified and carefully characterized. In the future, detailed investigation on non-stationary shock will be carried out using high-resolution data on interplanetary magnetic field and solar wind conditions provided by the MMS spacecraft quartet. This will lead to significant progress in understanding the shock transition layer.

References

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