Motion of the Earth's Bow Shock from Cluster

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Abstract

The dynamics of the Earth's bow shock is investigated using observations based on measurements made by the Cluster spacecraft quartet. A data collection of 133 Earth bow shock crossings, ranging from quasi-steady perpendicular to moderately noisy oblique geometries, have been identified and characterized using a timing method and the corresponding solar wind plasma conditions were collected. When present, the magnetic field fluctuations are suppressed using the conventional FFT technique prior the timing method is applied. The results of this investigation are compared with both Gas Dynamics and Magnetohydrodynamics bow shock models.

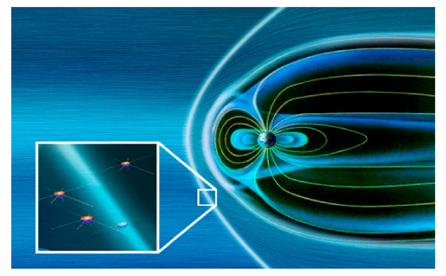
First, we have found that for half of the crossings, the timing and the conic-based shock normals agree within 11 degrees. Our results indicate that the motion is predominantly Sun-Earth directed. For shock speeds less that ~80 km/s, the shock velocity distribution fits quite well a Maxwellian profile with zero mean and a standard deviation of ~ 42 km/s. Higher shock speeds are usually associated with tangential discontinuities propagating in the solar wind. In this case, we show that the sharp increase observed in the ram pressure conducts to shock speed that are consistent with gas dynamics model predictions.

Motivation

- Analyzing shock motion with 4-point measurements.
- Comparison with model predictions.

Data Analysis Procedure

$$\begin{pmatrix}\vec{R}_1-\vec{R}_3\\ \vec{R}_2-\vec{R}_3\\ \vec{R}_4-\vec{R}_3\end{pmatrix}\bullet\frac{1}{V}\begin{pmatrix}n_x\\ n_y\\ n_z\end{pmatrix}=\begin{pmatrix}t_1-t_3\\ t_2-t_3\\ t_4-t_3\end{pmatrix}$$



R_1 , R_2 , R_3 and R_4 are the spacecraft position. t_1, t_2, t_3, t_4 the crossing time at each spacecraft.

- Determine the crossing time by analyzing the magnetic field.
- Timing Method.
- Cross-Correlation.
- Filtering.
- Plasma Data.

Plasma Data from ACE spacecraft

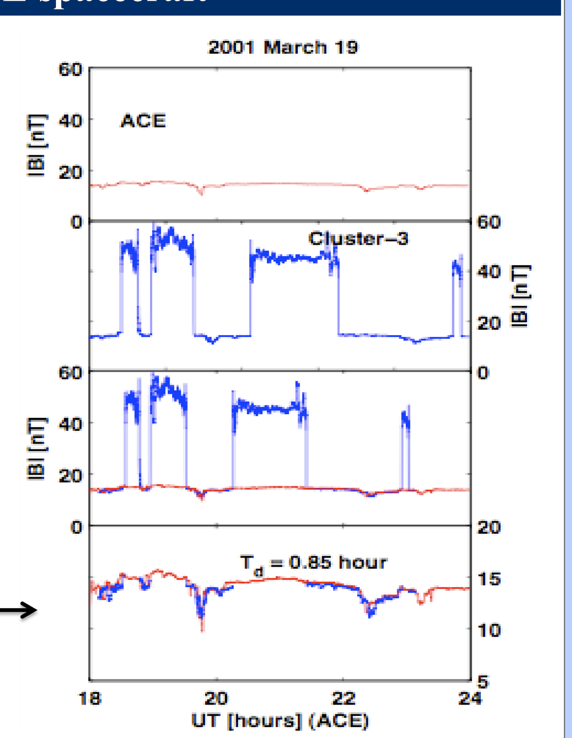
In case the plasma data are not available in Cluster database, we use ACE plasma data.

Time delay between ACE and Cluster.

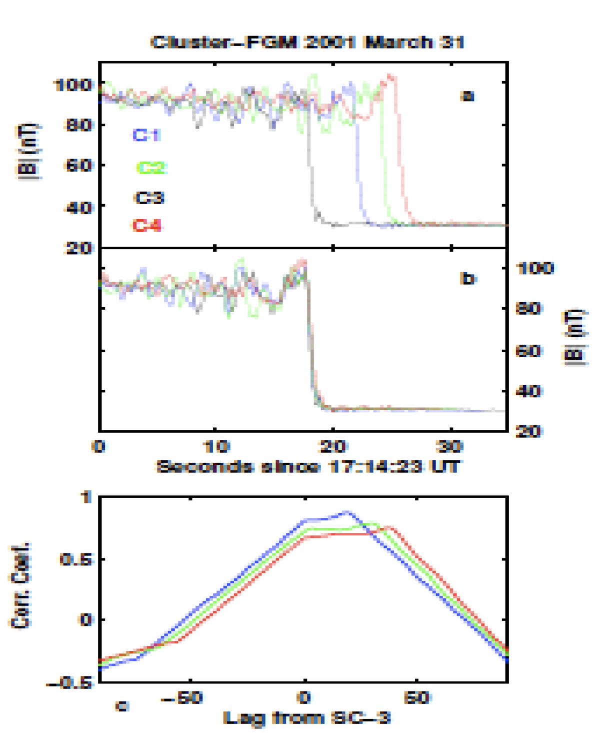
Magnetic field time series data from ACE.

Magnetic field time series data from Cluster-3.

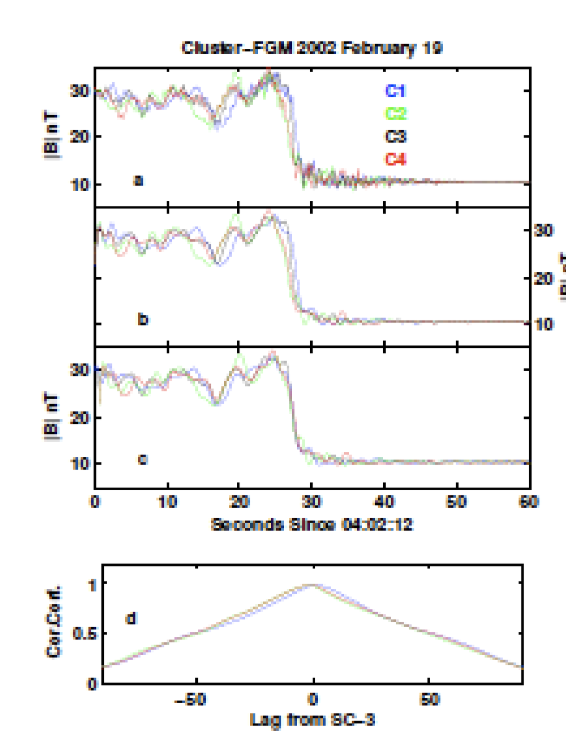
ACE+ Shifted Cluster (Δt = 0.85hrs) ⟶



Quasi-perpendicular Crossing



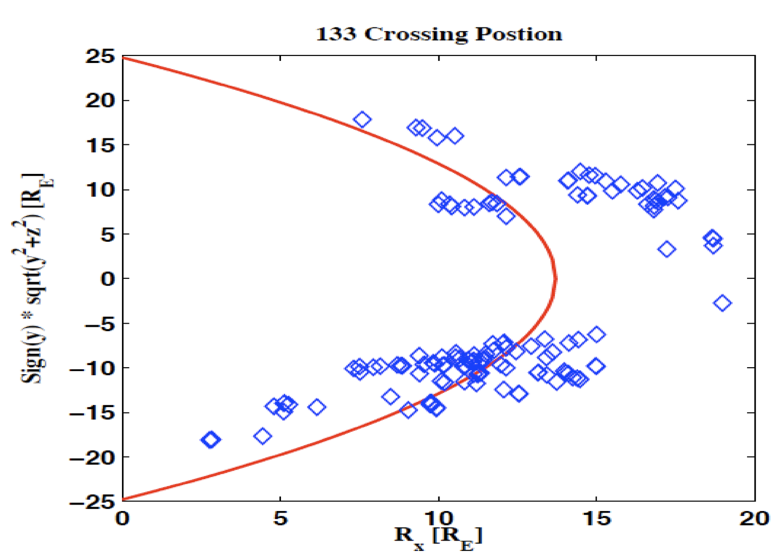
Moderately noisy oblique Crossing



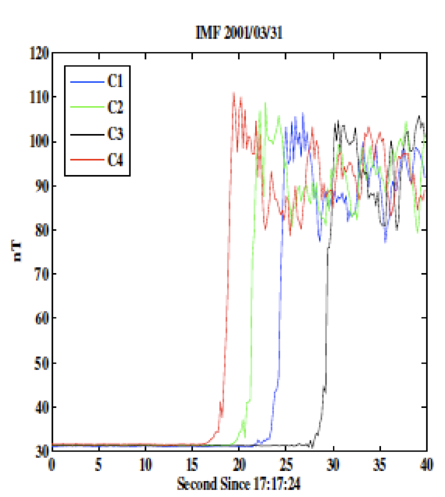
On The left: An example of clean bow shock crossing IMF measurement with Cluster-FGM on March 31, 2001 at 1739 UT. The middle panel shows the same profile shifted in time according to lags Δt, obtained from cross correlations between each spacecraft time series that of S/C3. The bottom panel provides those cross correlation values as function of lag.

On The right: Same as on the left for February 19,2002,in panel b,IMF fluctuation have been suppressed using FFT technique.

Observation and Database



Example of data analysis for 2001 March 31 17:17:24 – 07:18:07 UT



parameter	value
V_{sh}	49 km/s
θ_{BN}	82°
Δ_{t3-t1}	-4.4 s
Δ_{t3-t2}	-7.6 s
Δ_{t3-t4}	-10.2 s

parameter	value upstream
M_S	10.45
M_A	1.72
β	0.0190

Parameter	x	y	z
$\hat{n}_{gse}$	0.932	-0.153	0.328
$\vec{S}_{3gse}$	9.540	-1.475	8.997

M_A and M_s is the Alfvenic and sonic Mach number. β plasma, V_{sh} bow shock velocity, n_{gse} normal on the shock surface and S_{gse} spacecraft position and Δ_t is the difference in crossing time in second.

Standoff distance of the Earth's bow shock

- Standoff distance by Conics (parabolic) Model.

$$a_{st}=x+\frac{\sqrt{(1-n_x^2)(y^2+z^2)}}{2n_x}$$

The standoff distance a_{st} (R_E) in terms of the shock normal x-component (from timing method) and spacecraft position at the shock crossing (x,y,z) .

- Gas dynamics based model Standoff distance [Farris & Russell, 1994].

$$a_s=9.47\left(\frac{2}{\rho}\right)^{1/6}\left[1+1.1\frac{(\gamma-1)M_A^2+2}{(\gamma+1)(M_A^2-1)}\right]$$

ρ is the ram pressure in nPa, the parameters f and k reflect the effective portion of the solar wind dynamical pressure as applied to the magnetosphere and the effects of the electric current in the magnetopause, respectively; the numerical value of f^2/k is in the range 1.77 – 2.25; γ represent the specific heat ratio with a numerical value 5/3 and M_A is mach number.

- Magnetohydrodynamics based model standoff distance [Shue 1997]

$$a_s=\frac{1}{\rho^{1/6.6}}(11.4+\eta_z b_z)(1+1.1\frac{(\gamma-1)M_A^2+2}{(\gamma+1)(M_A^2-1)})$$

$$\eta_z\begin{cases}0.013 & b_z>0\\ 0.14 & b_z<0\end{cases}$$

This formula take the interplanetary magnetic field IMF b_z in account, for example, the magnetopause moves inward when the IMF is southward, and the standoff distance increases very slightly when the northward IMF increases.

Predict of The Earth's Bow shock Motion

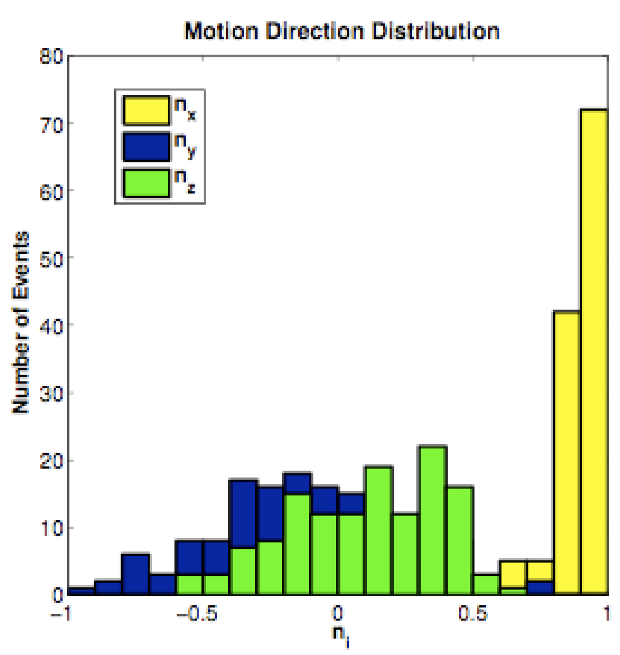
$$\frac{da_s}{dt}\approx-\frac{a_s\Delta\rho}{6\rho\Delta t}\left[1+\frac{13.2K}{a_s}\frac{\rho^{5/6}}{M_A}\left(\frac{M_A}{M_A^2-1}\right)^2\frac{\Delta M_A}{\Delta\rho}\right]$$

$$K=9.47\left(2\,{f^2}/{k}\right)^{1/6}$$

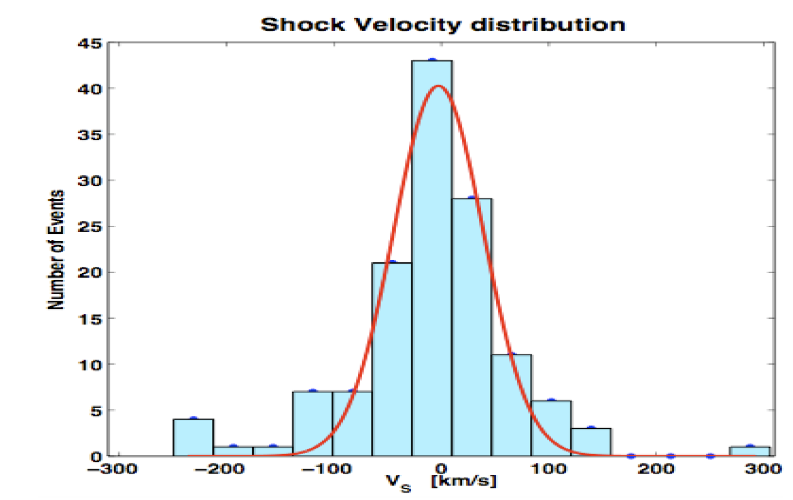
This equation provides the theoretical prediction of the shock velocity at the nose for given perturbations $\Delta\rho/\Delta t$ and ΔM_A . $\Delta\rho$ could be significant for propagating discontinuities which are quite common in the solar wind.

Statistical Results

The direction of shock motion. The figure shows the histogram for the measured shock normal GPE-components n_x , n_y and n_z . The distributions clearly indicate shock motion along the x-GPE axis strongly suggesting that the shock motion is basically along the Sun-Earth direction.



A



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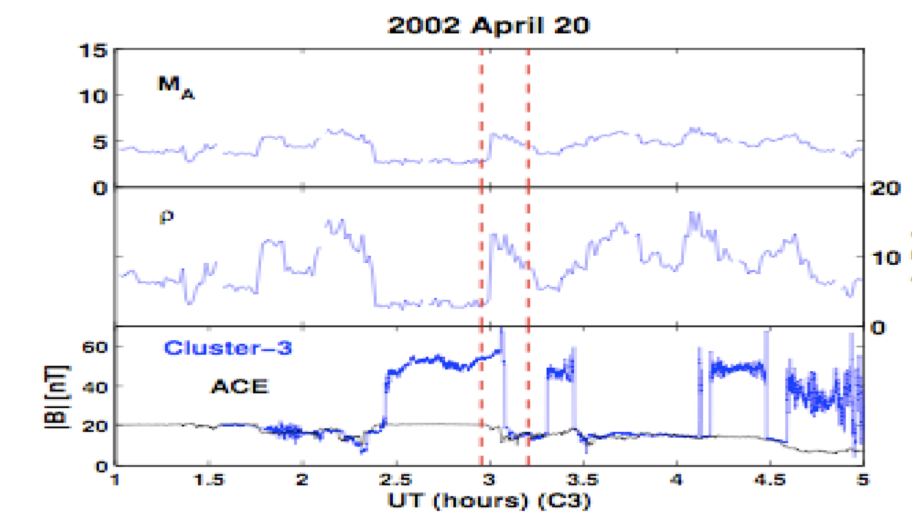

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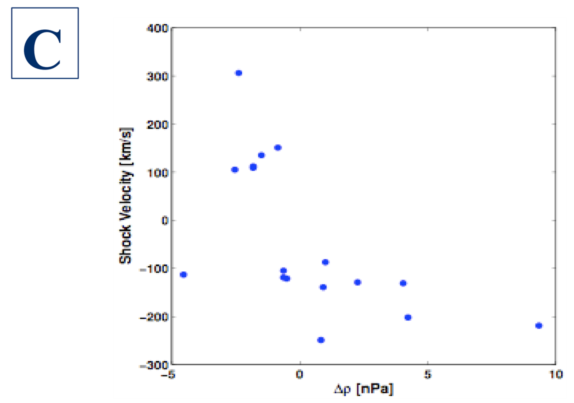

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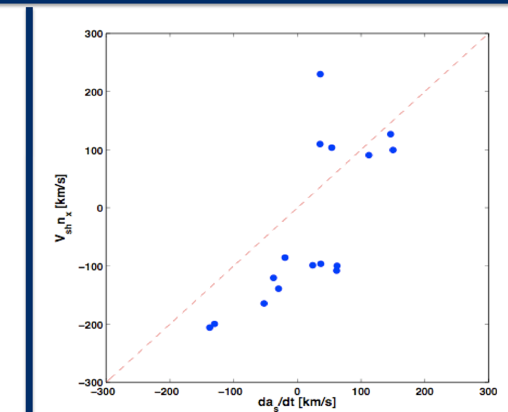

- **Figure (A):** The shock velocity distribution for 133 crossings, positive (negative) velocities correspond to outward (inward) moving shocks. The best Gaussian fit provided a mean of -2 km/s and a stander deviation equal to 42 km/s; departure from the Gaussian fit occurs at the speed of ≈ 80 km/s.
- **Figure (B):** Top panel shows magnetic field magnitude from Cluster-3 and ACE spacecraft on April 20 ,2002.Data from ACE are shifted by 42.4 minutes. The middle and bottom panels show measurements from ACE of ram pressure ρ , Alfven and Mach number M_A as derived from the solar wind and magnetic field data, respectively. the two dashed vertical lines in both panels indicates a 12 minute window centered on the shock crossing.
- **Figure (C)** Observed shock velocity is plotted versus the maximal numerical/algebraic value of $\Delta\rho$ within 12 min window.
- **Figure (D)** Observed shock velocity versus the model shock velocity predicted with (da_s/dt) equation. The dashed line has a slope of unity.

Conclusion

- Multi-Spacecraft observations are used to test models for the Terrestrial bow shock location and dynamics.
- Typical shock speed is about 42 km/s.
- The sharp gradients in ram pressure [Tangential discontinuities in the solar wind] cause fast shock speed. Weak dependence upon Mach number.