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On the shape and motion of the Earth's bow shock

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ABSTRACT

Multipoint-measurements by the magnetic field Cluster-FGM (Flux Gate Magnetometer) are used to determine the local shock normal, and in turn allow the study of shock location shape and the velocity of the Earth's bow shock. The shock crossings cover orbits in which the spacecraft separation is of the order of ~600 km or less. A data selection of 133 bow shock crossings, ranging from quasi-steady perpendicular to moderately noisy oblique geometries, have been analyzed using a standard timing analysis. Prior to applying the timing technique, the magnetic field fluctuations, when present, are suppressed using low band-pass filtering. The present study contributes to similar studies conducted in the past and available in the literature through the inclusion of a larger data set. The shock standoff distance is determined conjointly with a paraboloid model and the results from a timing analysis. A statistical study reveals a standoff distance well in agreement with the standard gas dynamics model prediction for high Mach number M_A. We have also found that for about half the crossings, the timing shock normals agree, within 11°, with a conic-based shock model. Our results strongly indicate that the motion of the shock is predominantly along the Sun–Earth direction; a departure from this direction is not related to the shock-crossing location. Shock velocities below ~80 km/s satisfactorily follow a nearly Gaussian distribution with zero mean and a standard deviation of ~42 km/s. Finally, we show that high speed motions are correlated with sharp increases in the solar wind upstream ram pressure, and are consistent with gas dynamics model predictions.

1. Introduction

The Earth's bow shock continues to attract intense theoretical and experimental investigations. It is believed that the study of the shape as well as the dynamics of the Earth's bow shock will lead to a better understanding of collisionless shocks in plasmas. Moreover, the Earth's bow shock constitutes a rare natural archetype of an irreversible transition boundary between plasma media, which suggests and justifies the relevance of bow shock studies. With an ever increasing data collection rate by space-born missions, numerous studies have been carried. This in turn has led to the availability of quality data with higher time resolution, including magnetic field, plasma and spacecraft potential, allowing sophisticated extensive analyses on the shape and position of the bow shock to be conducted.

It has been established that the bow shock shape and position are determined by the size and location of the magnetopause as well as the interplanetary conditions characterized by ram pressure, Mach number and IMF orientation. Early models using a geometric approach, but restricted to near ecliptic observations, were reported by Fairfield (1971). The first three-dimensional bow shock model was reported by Formisano et al. (1979): a study based on nearly 2500 crossings by HEOS-1, HEOS-2 and 5 IMP spacecraft, which revealed that the solar wind ram pressure is a controlling parameter as far as bow shock location is concerned. Numerous empirical models have been put forward since to predict the bow shock position as a function of the solar wind and IMF conditions. Over the past few decades, gas dynamics (Farris et al., 1991; Farris and Russell, 1994) and magnetohydrodynamics (Cairns and Lyon, 1995; Shue et al., 1997) models have been developed and tested against observations. Studies including the impact of the Mach number as well as the IMF orientation were reported by Peredo et al. (1995) and Merka et al. (2005). Various comparisons between models have been carried out (see Merka et al., 2003a,b and references therein). The statistical studies on the bow shock shape all assume a 2D surface with varying characteristics depending upon the interplanetary conditions (Němeček and Šafránková, 1991, Merka et al., 2005 and references therein). In particular, shock standoff distances have been derived from these models and discussed extensively.

Given the slow motion of the spacecraft, we assume that it is stationary and that crossings are a sole consequence of the bow shock motion. We also expect a significant departure from conics models, when the bow shock speed is high. Sharp changes in the

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solar wind parameters will drive the bow shock from one equilibrium state to another. Since the satellite location is taken as the bow shock equilibrium position when the satellite passes by, the real equilibrium position of the bow shock is not properly determined.

Moreover, progress in numerical simulations of shocks (Lembége et al., 2009), and in recent observations (Mazelle et al., 2010), strongly indicate that the departure from equilibrium may be caused by the non-stationarity of the shock. In particular, and for a large range of Mach numbers, quasi-perpendicular shocks suffer a self-reformation process which results in non-negligible variations of the shock front speed. This process may occur without any variation of the solar wind parameters. Up to now, shock motions resulting from self-reformation have been out of reach for as far as investigations are concerned.

To a lesser degree, the motion of the bow shock has also received some attention (Formisano et al., 1971; Guha et al., 1972; Němeček et al., 1988; Lepidi et al., 1996). Shock motion may result essentially from various disturbances in the solar wind conditions. A theoretical study by Völk and Auer (1974) has shown that the interaction of the solar wind Alfvèn waves with the shock generates a shock motion of relatively low speed (~ 10 km/s), whereas tangential discontinuities hitting the shock cause motions with much higher speeds. Earlier observations of bow shock motion were reported by Formisano et al. (1971) and Guha et al. (1972) who found shock speeds in the 50–150 km/s range. However, we should point out that these determinations result from single spacecraft measurements, and are therefore subject to significant uncertainties.

Two-point measurements of bow shock speed have also been reported by Zastenker et al. (1988). Given the significantly large spacecraft separation ($\sim 20R_E$) in this particular study, These last authors suggested that, at a given location, the shock triggers a surface wave moving along the shock front. Using data from the ISEE1 and 2 spacecraft data, Newbury et al. (1998) estimated shock velocities assuming magnetic coplanarity. Huterer et al. (1997) analyzed nine IMP 8 bow shock crossings and found that the shock motion is on average consistent with the “breathing” model of shock motion. Šafránková et al. (2003) analyzed 130 bow shock crossings by the closely separated spacecraft MAGIO-4/INTERBALL-1 and suggested that 80% of the estimated velocities are consistent with radial expansion/compression of the shock surface. Interestingly, this last study indicated that slow shock velocities (≤ 5 km/s) are observed during quite upstream conditions, and that the probability of observing high speed shocks increases during disturbed IMF conditions, suggesting in turn that the Mach number is the dominant factor rather the variations in ram pressure. Finally, we should mention that shock oscillations around an average position may also result from intrinsic shock non-stationarity, which occur at high Mach number.

Before the Cluster mission, all shock motion measurements were performed using data collected by single or dual spacecrafts whether the Rankine–Hugoniot equations are used or not. With the Cluster quartet, full three-dimensional shock velocities as well as shock normal were determined for the first time. Horbury et al. (2002) were the first ones to use high time resolution magnetic field from Cluster to study the shape and the motion of the shock. From a selected sample of 48 quasi-perpendicular bow shock crossings, these authors determined the shock normal using a timing method (Schwartz, 1998). The method allows for a satisfactory determination of the local shock normal when the spacecraft separation is less than the shock curvature and when the shock acceleration is negligible. With the timing technique, a reliable determination of the local shock normal requires the distance between the quartet elements to be relatively small, given that ripples and surface waves may cause significant deformation. Maksimovic et al. (2003) applied the same timing technique to successive crossings, which occurred on March 31, 2001, and compared the observational results to a gas dynamic bow shock model. The same analysis was also applied when the distance between the four Cluster spacecraft was the smallest, and in which the shock normal was investigated (Mazelle et al., 2010).

In this current study, we have tried to focus primarily on shock motion by extending the previous studies to a larger data set. The next section briefly describes the data set as well as the analysis technique used; examples of shock crossings are also presented in the same section. Section 3 is devoted to statistical results, and a discussion and conclusion are presented in the last two sections of the document.

2. Data selection and analysis

The study is based on magnetic field data measurements from the Cluster-FGM experiment (Balogh et al., 2001). The high time resolution data was downloaded from the Cluster Active Archives on the ESA website. In order to avoid shock shape distortions, only orbits with small spacecraft separation were considered. This covers cusp orbits in years 2001 and 2002. In all bow shock crossings, we used a time resolution of 5 vectors/s (5 Hz).

It is clear that the appearance of the ramp profiles, which are superposed and used to verify the crossing times for the four spacecraft, depends upon the time resolution chosen in the analysis. The use of 5 Hz data is usually good enough, when the spatial ramp thickness is not too small. However, some recent studies have shown that the thickness of the shock ramp could be very small and highly dynamic (Mazelle et al., 2010; Hobara et al., 2010). We should mention that, while conducting the analysis, we were primarily interested in the bulk characteristics of the shock rather than the kinetic scale features. This is clearly reflected by our choice of the magnetic field data time resolution which enabled us to determine the shock normal within the domain of validity of the MHD approximation. The purpose in the present is to determine the global motion of the shock front.

Other parameters of interest, including Mach numbers and ram pressure, are used and were derived from plasma data. To calculate these parameters, we have used measurements from ACE/SWEPAM and Cluster/CIS, respectively. For the latter, only measurements from the low-geometry factor analyzer (HIA instrument), when available, are considered in the present study. When in the solar wind mode of operation, the Cluster/CIS-HIA analyzer captures the velocity space centre of the solar wind beam. As mentioned above, the time delay between successive crossings is determined using the conventional technique of timing difference (Schwartz, 1998), whose domain of validity and restrictions are discussed in detail by Horbury et al. (2002). This method assumes that the bow shock structure is planar on average, similar for all spacecrafts, and that the shock velocity is constant while crossing the cluster formation. However, in many cases, shock structures may appear more developed in one spacecraft than in the others, during the same crossing sequence. For instance, during a same supercritical shock self-reformation cycle, the foot and the overshoot as well the ramp suffer a significant change in terms of size. However, we again focus on the MHD-like scales in the determination of the shock characteristics in average, similar for all spacecrafts, and that the shock velocity is constant while crossing the cluster formation. For each crossing, an automatic procedure computing the cross-correlation of the IMF signals is applied to find the accurate time delay between the spacecraft signals. To improve the determination of the time delay, high frequency-IMF fluctuations (when present) are removed or suppressed using appropriate techniques such a low band-pass filtering or moving averages. The present study uses a data set of 133 shock crossings carefully selected. The plasma data in the solar wind (upstream) are taken from the Cluster/