Chapter 4

Cluster at the Bow Shock: Introduction

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The terrestrial bow shock is formed in the solar wind when the supersonic plasma emitted from the Sun encounters the Earth's magnetic field. The dipole magnetic field of the Earth acts, in the first approximation, as an impenetrable barrier to the solar wind which therefore has to slow down and flow around the obstacle. In this process, the magnetopause is formed, separating the magnetic field inside from the solar wind that flows around it. Ahead of the magnetopause, the bow shock forms a surface across which the solar wind plasma is heated and slowed down from supersonic to subsonic speeds. The Earth's bow shock is the best known and most studied example of a collisionless plasma shock and has been the subject of extensive observational and theoretical investigations since the start of the space age (see, e.g., Fairfield, 1976; Tsurutani and Stone, 1985; Burgess, 1995; Russell, 1995, and references therein). Collisionless plasmas make up a large fraction of

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the astrophysical world. Shocks are believed to play critical roles in flow dynamics and heating under a wide variety of circumstances as well as providing prime acceleration environments for cosmic rays.

The overall, schematic view of the average location and shape of the bow shock is shown in Figure 4.1 (see, e.g., Formisano, 1979; Peredo et al., 1995). A typical distance from the Earth to the subsolar point of the bow shock is $\sim 14R_e$, but the location of the bow shock is highly variable, dependent on the speed and density of the solar wind. In general terms, the large scale geometry of the bow shock depends on the solar wind pressure. As for all collisionless plasma shock waves, the nature of the shock transition from supersonic to subsonic flow depends, primarily, on two parameters. One is the Mach number of the shock wave, the ratio of upstream velocity to the characteristic wave speed (e.g., Alfvén or magnetosonic); for the terrestrial bow shock this is usually in the range from ~ 3 up to 10. The second is the angle θ_{Bn} between the upstream magnetic field direction and the normal direction to the shock surface. The physics within the transition is also influenced by the upstream plasma β (the ratio of the thermal pressure to magnetic pressure).

The manner in which the dominant plasma heating and dissipation that occur at the shock transition depends on θ_{Bn}. Figure 4.1 shows the average direction of the interplanetary magnetic field lines upstream of the bow shock. Across the surface of the bow shock, θ_{Bn} ranges from close to 90° to close to 0° (or from quasi-perpendicular to quasi-parallel). In the quasi-perpendicular case, the shock transition tends to be abrupt in time (in the frame of the solar wind) and spatially well-defined, although the detailed physics within the shock layer involves multi-scale, time-dependent phenomena. In the quasi-parallel case, the transition occurs over an extended region which contains inhomogeneous and transient field and shock-related particle features.

The average direction of the interplanetary magnetic field shown in Figure 4.1 is in fact a gross oversimplification of the conditions actually observed upstream of the bow shock. Both the direction and strength of the IMF, together with other plasma parameters, are highly variable on a range of spatial scales relative to the dimensions of the bow shock. Accordingly, the geometry (quasi-parallel vs. quasi-perpendicular) and Mach number of individual relatively rapid shock transitions are controlled by the prevailing solar wind conditions.

Studies of the bow shock using single- and dual-spacecraft observations are too numerous to quote here individually (see, e.g., Thomsen, 1988). Equally, many theoretical and numerical modelling investigations have addressed the different aspects of the bow shock formation, structure, parametric dependence and dynamics (selected recent advances can be found in Lembège et al., 2004, and references therein).

Such single or two-point studies have intrinsic limitations. The bow shock is in constant motion as it moves in and out in response to changes in the solar wind ram pressure at speeds of ~ 5 to over 100 $\mathrm{km\,s^{-1}}$ (Lepidi et al., 1996). Its struc-

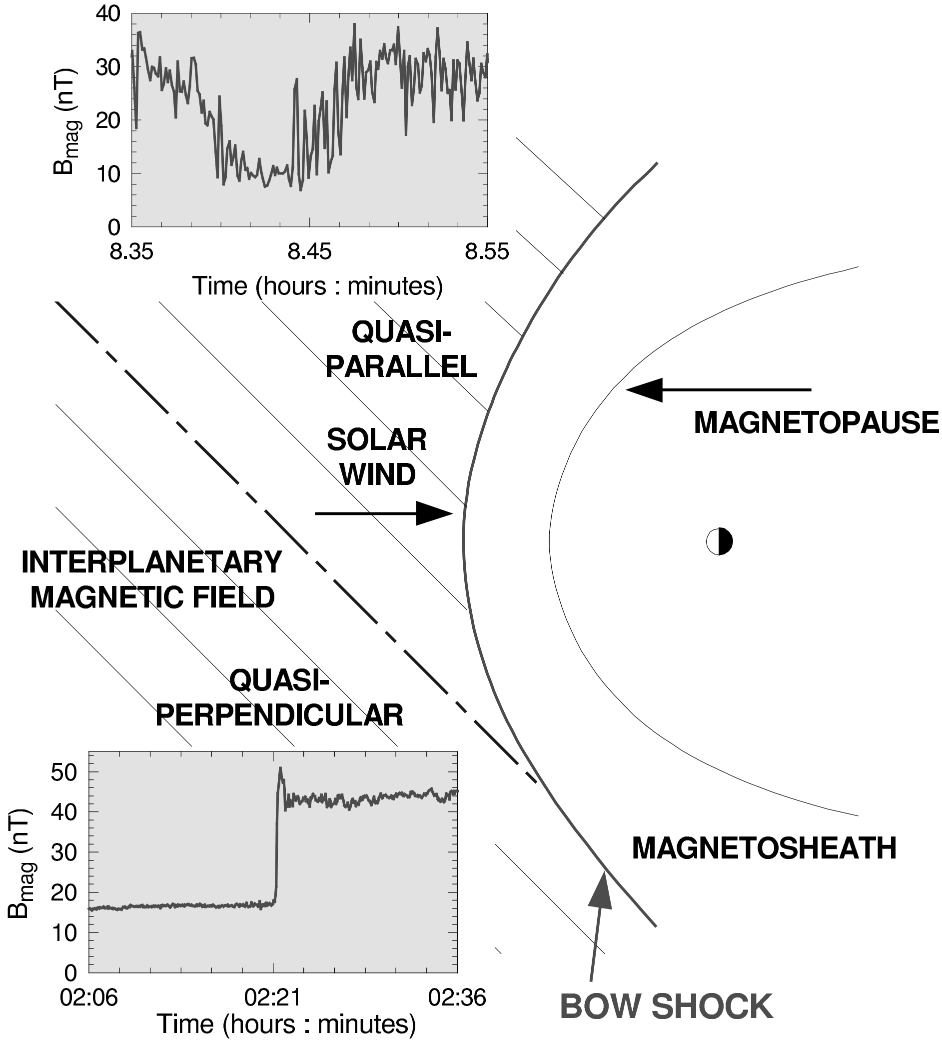

Figure 4.1. Sketch of the Earth's bow shock ahead of the magnetosheath and magnetosphere. The angle between the direction of the interplanetary magnetic field lines and the normal to the shock surface ranges (for the average direction of the IMF shown here) from quasi-parallel on the dawn side to quasi-perpendicular on the dusk side of the bow shock. The scales of the shock transition and dissipation regions are significantly different for the quasi-perpendicular and quasi-parallel cases as illustrated by the insets showing the evolution of the magnetic field magnitude measured by Cluster across two shock transitions. Figure provided by A. Balogh.

ture is also variable, mainly in response to local changes in θ_{Bn} and to magnetic and plasma structures swept into the shock by the solar wind. Relatively small directional changes in the IMF, as it is swept against the bow shock surface, may alter the physical parameters that would be observed at a small distance away from the actual crossing. Single- and dual spacecraft observations have clarified many properties of the bow shock under most conditions and described many details of its phenomenology. However, many of the quantities that are needed to describe the bow shock processes are related to spatial derivatives, such as the geometry of the shock surface, associated wave fields and the shock's velocity. The determination of such quantities using single spacecraft measurements requires supporting assumptions that may be approximately suitable or even questionable. Statistical studies of many observations have, however, alleviated some of the inherent shortcomings of single spacecraft measurements (Peredo et al., 1995).

The four-spacecraft measurements of Cluster have been able to contribute to many of the topics that are related to the physics of the bow shock. First, by making the first detailed, three-dimensional studies of individual shock crossings, the phenomenology and physical processes within and in the vicinity of the bow shock, under specific conditions, could be clarified. Second, through the ability to make unambiguous determinations of the vector quantities associated with the shock it has been possible to underpin and re-examine the statistical studies of shock motion, and both local and overall shock orientation.

The Cluster data set, now extending over four years from late 2000, has proved to be very rich. Single- or even dual-spacecraft observations and studies have not proved to be a fully adequate preparation for the complexity observed at all the separation scales near the bow shock. New methodology had to be developed (e.g. Paschmann and Daly (eds.), 1998) and tested alongside previously used methods, and new ideas confronted by the observations. Cluster has explored spatial scales from $\sim$ 100 km to 5000 km and this range will be extended to 10,000 km and beyond before the end of the mission. At all these scales, new phenomena were observed at shock crossings with potential implications for new aspects of shock physics to be studied in the future.

In a number of topics, the contribution by Cluster is already significant. These topics are extensively discussed in the following chapters.

- **Definitive studies of absolute shock scales: variations with shock parameters**
  Cluster studies have measured the width of the ramp at the quasi-perpendicular bow shock over a range of upstream parameters (Mach number, etc.). The width is a critical indicator of the internal shock processes which in turn govern the partition of energy amongst the incident particle populations.

- **Temporal/spatial variability: motion and internal dynamics**
  Cluster determination of the speed of the bow shock has shown that variations

in the upstream parameters have an immediate and direct impact on the location and gross motion of the shock. However, Cluster electric and magnetic field observations have also highlighted considerable variability in the shock structure and profile even over relatively small scales associated with particle kinetic behaviour.

- **Proof that ion beams manage to emerge from particles reflected at quasi-perpendicular shocks**
  Simultaneous Cluster ion observations at several locations have provided unambiguous evidence that field aligned beams found upstream of the quasi-perpendicular bow shock emerge out of the reflected and partially scattered population at the shock itself rather than originating deeper in the magnetosheath.

- **Surprisingly small-scale structure within large (discrete?) entities at quasi-parallel shocks**
  Cluster measurements of large-amplitude magnetic structures which are believed to be an integral part of collisionless shocks under quasi-parallel conditions have revealed the surprising result that they appear quite different even at scales 10% of their overall size. Moreover, these differences are not the same in the electric and magnetic components. Thus the previously-believed monoliths are in fact quite filamentary.

- **Determination of spatial gradients of diffuse energetic ions, and hence a definitive measure of the scattering mean free path**
  Spatial gradients of diffuse ions in the foreshock have provided a direct measure of the scattering mean free path in the self-consistent local turbulence. Thus the first order Fermi acceleration of particles in these regions can be quantified.

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