Chapter 5

Quasi-perpendicular Shock Structure and Processes

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5.1 Introduction

In the two decades prior to the launch of Cluster, collisionless shocks at which the magnetic field in the unshocked plasma is nearly perpendicular to the shock normal (‘quasi-perpendicular shocks’) received considerable attention. This is due, in part, to their relatively clean, laminar appearance in the time series data. The tendency of the magnetic field to bind particles together owing to their (perpendicular) gyromotion gives rise to this appearance, which facilitated deeper studies into the collisionless processes responsible for the overall thermalization of the principle plasma populations as well as the acceleration of an energetic non-thermal component. Despite the considerable effort, key questions remained unanswered or re-
mained open to interpretation. Single, and at best dual, spacecraft studies were unable to place quantitative limits on the important spatial scales, nor assess the role of non-stationary aspects in the overall shock transition.

By taking advantage of the sharp, quasi-perpendicular shock transitions, Cluster investigations have been able to address the shock orientation and motion via now-standard four spacecraft techniques. As a consequence, Cluster has been able to probe the internal shock scales (and hence physics). Additionally, the multi-spacecraft strategy has enabled definitive studies of where energetic particles do, and don’t, come from. This Chapter summarises many of these achievements.

5.2 Structure and Thermalization

5.2.1 Bow shock orientation and global structure

Knowledge of the basic parameters of a shock, such as Mach number and angle $\theta_{Bn}$ between the shock normal and (unshocked) magnetic field, is essential for a quantitative analysis of shock dynamics. However, such parameters are often difficult to determine in practice since they require both accurate measurement of plasma and field values around the shock, as well as estimates of characteristics of the shock itself. Most obvious among the latter are the shock orientation and speed. These parameters are difficult to estimate with a single spacecraft, although various techniques such as coplanarity (e.g., Schwartz, 1998) can be used to estimate the shock orientation. New methods of determining shock orientation and speed are therefore of interest.

The measurement of the same shock transition by the four Cluster spacecraft in close succession allows us to estimate the orientation and velocity of the structure in several ways which have not previously been possible. Each of these methods requires assumptions to be made about the properties of the shock, and each has advantages and disadvantages in different situations. A number of such methods have been applied to Cluster crossings of the quasi-perpendicular bow shock, as we report below.

5.2.1.1 Comparison of methods to determine shock orientation

Horbury et al. (2002) used four spacecraft timings of magnetic field data to estimate the orientation of the quasi-perpendicular bow shock at a number of crossings and compare these results with magnetic coplanarity estimates as well as orientations predicted by parametric models of the large scale bow shock shape.

If we assume the shock to be planar on the scale of the spacecraft separations, and to be travelling at a constant speed as it passes over the four spacecraft, then the times at which it crosses them can be used to estimate the normal of the shock plane and the speed at which it is travelling along that normal (see Dunlop and Woodward, 1998, for more details). These assumptions will not always be satisfied. Non-planarity of the shock can be caused by large scale curvature or by rippling