Ann. Geophysicae 17, 1560–1573(1999) © EGS – Springer-Verlag 1999

Annales Geophysicae

Identification of magnetosheath mirror modes in Equator-S magnetic field data

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Received: 10 March 1999 / Revised: 30 June 1999 / Accepted: 20 July 1999

Abstract. Between December 1997 and March 1998 Equator-S made a number of excursions into the dawn-side magnetosheath, over a range of local times between 6:00 and 10:40 LT. Clear mirror-like structures, characterised by compressive fluctuations in $|B|$ on occasion lasting for up to 5 h, were observed during a significant fraction of these orbits. During most of these passes the satellite appeared to remain close to the magnetopause (within 1–2 Re), during sustained compressions of the magnetosphere, and so the characteristics of the mirror structures are used as a diagnostic of magnetosheath structure close to the magnetopause during these orbits. It is found that in the majority of cases mirror-like activity persists, undamped, to within a few minutes of the magnetopause, with no observable ramp in $|B|$, irrespective of the magnetic shear across the boundary. This suggests that any plasma depletion layer is typically of narrow extent or absent at the location of the satellite, at least during the subset of orbits containing strong magnetosheath mirror-mode signatures. Power spectra for the mirror signatures show predominately field aligned power, a well defined shoulder at around 3–10×10^{-2} Hz and decreasing power at higher frequencies. On occasions the fluctuations are more sinusoidal, leading to peaked spectra instead of a shoulder. In all cases mirror structures are found to lie approximately parallel to the observed magnetopause boundary. There is some indication that the amplitude of the compressional fluctuations tends to be greater closer to the magnetopause. This has not been previously reported in the Earth's magnetosphere, but has been suggested in the case of other planets.

Key words. Magnetospheric physics (magnetosheath; plasma waves and instabilities; magnetopause, cusp and boundary layers)

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1 Introduction

Between December 1997 and March 1998 the Equator-S satellite crossed into the magnetosheath during at least 31 orbits (initially surveyed by Dunlop *et al*., 1999, and hereafter referred to as paper 1). The magnetosheath observations extend from 06:00 to 10:40 LT and, as the orbit evolves dawnwards, they become biased towards higher solar wind ram pressure (P_{RAM}). With an orbital apogee of 11.5 Re, the satellite remained in the magnetosheath for many hours, within 1–2 Re of the magnetopause, during several of the orbits, and was therefore well positioned to observe wave activity in this region of the dawn-side magnetosheath. Examination of the magnetic field data recorded by the MAM experiment (paper 1) showed that approximately 30% of orbits contained strongly compressional magnetic field signatures in the magnetosheath, often located within a few minutes of the magnetopause. Lucek *et al*. (1999) (hereafter referred to as paper 2) briefly surveyed these events, showing that they were consistent with mirror structures.

Under conditions of temperature anisotropy (where $T_\perp > T_{||}$), two types of plasma instability can operate which generate low frequency waves (i.e. the wave frequency lies below the proton gyro-frequency (Ω_i)). One of these, the ion cyclotron instability, dominates under conditions of high temperature anisotropy (when the parallel proton temperature ($T_{||p}$) is low), and the proton plasma beta (β_p) ~ 1, and generates transverse electromagnetic ion cyclotron (EMIC) waves through a resonant wave particle interaction. The fastest growing modes are those propagating in a direction parallel to the background magnetic field (i.e. the angle between the wavevector and the field direction (θ_{kB}) $\sim 0°$, e.g. Schwartz *et al*., 1996). High frequency EMIC waves ($f \sim 0.5$–$1\ \Omega_i$) are generally found to be left-hand circularly polarised, but lower frequency waves can be linearly polarised (Anderson *et al*., 1991; Anderson and Fuselier, 1993). The second instability to operate under conditions of temperature anisotropy is the mirror instability. The growth rates of EMIC waves would be expected to dominate those of mirror structures in a purely proton plasma, but the presence of additional cold ion species, such as helium, is thought to suppress the ion cyclotron instability (Price *et al.*, 1986; Gary *et al.*, 1993). Empirically, therefore, the mirror instability dominates under conditions of moderate temperature anisotropy and high beta, and generates strongly compressive (frequently showing $\Delta B/B \sim 1$), linearly polarised, non-propagating structures. Within the structures, the plasma and magnetic pressures are anti-correlated. If the plasma just exceeds the condition for stability to mirror waves, then the fastest growing modes are those with θ_{kB} close to 90°. For larger temperature anisotropy (>2) the growth rate is highest for modes propagating obliquely ($\theta_{kB} \sim 60°$) (Price *et al.*, 1986). There is also some evidence from simulations to suggest that as mirror structures evolve, they move to longer wavelengths (scale size ~20 proton gyro-radii) (McKean *et al.*, 1994), and that saturated mirror structures can give rise to larger amplitude magnetic field enhancements (e.g. Schwartz *et al.*, 1996).

In the magnetosheath there are two mechanisms which can be seen to generate a temperature anisotropy where $T_\perp > T_\parallel$: gyratory ion motion arising from reflected ions at the bow shock under quasi-perpendicular conditions, and compression of the magnetosheath field close to the magnetopause. Close to the nose of the magnetosphere, for instance, especially under conditions of northward IMF (giving conditions of low magnetic shear at the magnetopause), alignment of the magnetosheath field with the magnetopause arises from transverse IMF orientations (quasi-perpendicular conditions near local noon). Plasma pileup leads to a region of both depleted plasma density and an enhanced magnetic field intensity lying adjacent to the magnetopause (e.g. Wu, 1992). This region, where the temperature anisotropy is high and β is moderate, is called the plasma depletion layer (PDL), or sometimes the magnetopause transition layer (e.g. Phan *et al.*, 1994) and is generally found to be unstable to the growth of circularly polarised EMIC waves (e.g. Anderson *et al.*, 1991, 1994; Anderson and Fuselier, 1993; Hubert *et al.*, 1989; Phan *et al.*, 1994); but stable to mirror mode growth. Outside of the PDL the magnetosheath is often found to be unstable to the growth of mirror structures (e.g. Anderson and Fuselier, 1993; Anderson *et al.*, 1994; Phan *et al.*, 1994). These studies show that close to the subsolar point the region identified as a PDL generally lasts for between 10 and 30 min between the magnetopause crossing and the onset of mirror-like activity. The PDL tends to be absent under conditions of radial IMF and/or southward IMF (when transport across the magnetopause is likely to be high). The implied field geometry, however, is most relevant to the equatorial region near local noon, rather than the flanks.

Paper 2 illustrated the typical features of the magnetosheath mirror-like structures in Equator-S data by presenting data from one long interval of mirror-like activity, lasting for about 5 h and occurring at ~9:00 LT. A more comprehensive account of the occurrence and nature of the magnetosheath signatures will be given here. Intervals of mirror-like activity identified to date are listed and a number of selected events are also discussed in some detail. Mirror structures have been identified in spin-averaged data (~0.67 vectors/s) primarily by the occurrence of large amplitude ($\Delta|B|/|B| \sim 0.25$–1) fluctuations in the magnetic field magnitude, within a low frequency envelope, together with a maximum variance direction (for the de-trended field) which was closely aligned with the background (DC) magnetic field direction. It is expected that clear mirror structures will be identified using these criteria, but marginal cases might be missed without the plasma data for confirmation.

Since the Equator-S magnetosheath data are mainly recorded near the magnetopause, intervals of mirror-like activity are likely to be associated with the magnetic field configuration close to the magnetopause, rather than temperature anisotropy generated at the bow shock. There are a few orbits however, where the magnetosheath data within an hour or so of the magnetopause show no clear evidence for either a PDL or mirror activity, but later in the interval some mirror activity is observed (paper 1). These intervals of mirror activity are documented for completeness, but are more likely to be related to conditions at the bow shock rather than conditions of the magnetosheath close to the observed magnetopause, or large changes in the local magnetopause conditions.

2 Overview

As discussed in paper 2, compressive magnetic field signatures consistent with mirror mode structures occur on approximately 30% of orbits where the satellite entered the magnetosheath and these are shown in Fig. 1. This figure shows an overview, projected onto the $(X,Y)_{GSE}$ plane, of the locations in LT of the intervals of mirror-like activity (heavy lines) within the Equator-S orbits (dotted lines), and the associated magnetopause crossings (open squares). It is clear from the figure that several of the intervals of mirror activity are long, up to 5 h. The figure also shows cuts through two nominal magnetopause locations (Sibeck *et al.*, 1991) at a height Z_{GSE} above the $(X,Y)_{GSE}$ plane which is representative of the crossings, one under conditions of low solar wind pressure ($P_{RAM} \sim 1.8$ nPa) and the other for high P_{RAM} (9 nPa) (see paper 1). These show that as the spacecraft moved to earlier LT, the magnetopause crossings are biased to higher P_{RAM}. It is important to note, however, that the magnetopause cuts do not represent actual magnetopause positions at the times of the crossings. Nevertheless, most intervals clearly occur around apogee.

In papers 1 and 2 it was commented that the distinguishing feature of the Equator-S orbits containing clear mirror-like signatures was the large proportion showing mirror activity continuing undamped to within a few minutes of the magnetopause, and the general absence of signatures consistent with a well developed