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THEMIS observations of mirror structures: Magnetic holes and instability threshold

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[1] Nonpropagating mirror-mode structures are commonly observed in many regions of natural plasma such as solar wind, planetary magnetosheaths, in cometary plasma, Io wake, terrestrial ring current and even on the outskirts of solar system. Mirror structures are typically observed in the shape of magnetic holes or peaks. Fast survey mode plasma data from the THEMIS satellites are used to solve the puzzle of how mirror structures in the form of dips can be observed in the regions of mirror stable plasma. THEMIS data also show that for mirror structures with spatial scales that considerably exceed ion Larmor radius the perpendicular temperature anticorrelates with the strength of the magnetic field. This contradiction with the conservation of adiabatic invariants is explained by the role of trapped particles.
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1. Introduction

[2] Nonpropagating mirror structures are commonly observed in many regions of natural plasma such as the solar wind, planetary magnetosheaths, in the vicinity of comets, the Io wake, terrestrial ring current, and even on the outskirts of the solar system. Interest in mirror modes originated in studies of the stability of laboratory plasma configurations related to fusion devices, in particular Θ-pinches, well before spacecraft observations of in-situ mirror waves attracted attention. In the very beginning a fully kinetic approach to the mirror instability was developed by *Vedenov and Sagdeev* [1958], who pointed out that the mirror instability is not hydrodynamic in nature but is in fact a resonance instability in which the resonant ions have small parallel velocity and as a result non-propagating structures are generated. However, a reduction of interest in controlled fusion led to a diminishing interest in the mirror instability. Research activities were reignited by ISEE observations of mirror mode structures in the terrestrial magnetosheath and in the vicinity of comets [*Russell et al.*, 1987; *Tsurutani et al.*, 1999]. A consequence of this time gap when interest in mirror wave studies waned was that the initial kinetic treatment of the mirror instability was almost completely forgotten and many researchers subsequently treated mirror instability from a hydrodynamic standpoint. It was *Southwood and Kivelson* [1993] who reminded researchers of its resonant nature and the necessity for a fully kinetic treatment. Since then, substantial progress in the theory of the mirror instability has been achieved. The quasi-hydrodynamic treatment developed by *Southwood and Kivelson* [1993] that accounts for the resonant nature of the mirror instability has used to determine the effects of finite electron temperature and multi-component plasmas on the linear stage of the mirror instability [*Pokhotelov et al.*, 2002; *Gedalin et al.*, 2002]. A fully kinetic treatment to describe the mirror instability in a non-Maxwellian plasma was used by *Pokhotelov et al.* [2004] to account for finite Larmor radius (FLR) effects. However, despite all the progress that has been made regarding the dynamics of the observed mirror waves, a comprehensive insight into the mechanism of the mirror instability is far from completely clear. The evolution of the mirror instability during the nonlinear stage is still highly controversial. Two basic approaches have been adopted. *Kuznetsov et al.* [2007] assumed that any modification of distribution function caused by ion trapping can be neglected. This effectively means that the mirror instability has an unlimited source of free energy which ultimately results in collapse like dynamics. On the other hand, *Pokhotelov et al.* [2008] claim that modification of the distribution function and particle trapping leads to a decrease in the number of resonant particles and hence stabilization. The evolution of the experimentally observed mirror structures is also far from clear. Mirror waves usually appear as nonlinear structures either as magnetic holes (i.e., depressions or dips in $|B|$) or enhancement (peaks) of the magnetic field. A number of experimental studies have pointed out that magnetic dips/peaks exist in low/high β plasma [*Soucek et al.*, 2008]. It has been argued on the basis of Cluster data that magnetic holes are typically observed when the plasma β and temperature anisotropy are too low for the mirror instability to be excited, i.e., during periods when mirror structures should decay. However, the time resolution of the Cluster plasma parameters used in these studies is much less than the typical duration of mirror dips observed in the terrestrial magnetosheath. The importance of this fact for nonpropagating mirror waves can be understood using a simple thought experiment. Consider a region of plasma in which the parameters are such that the threshold of a particular instability is not satisfied and let these parameters evolve towards the threshold of instability. Since a real plasma is not uniform, the localized parameters will vary with respect to spatially averaged values and so in some locations the instability condition will be satisfied whilst in others the plasma remains stable. If a plasma

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wave is generated at some unstable location, it will grow as it propagates through the unstable region. Once the wave has left the unstable region and entered a stable one it will begin to decay, only starting to grow again if it reaches another unstable region. As a result, the plasma wave will be observed with properties (growth rate, direction of propagation, polarization etc) reflecting the average plasma parameters in the regions. However, in case of non-propagating mirror waves the situation will be different. Since the instability threshold will be exceeded in some locations, the wave generated will remain in the same location with properties corresponding to the local conditions. Isolated magnetic holes are usually observed embedded in regions in which any mirror waves are absent. Therefore, if the threshold condition is averaged over a large region in which magnetic holes occur intermittently and the periods between the mirror structures are long in comparison with the period of the mirror structures the resulting plasma parameters will lead to an underestimation of the threshold for locations at which the magnetic dips are observed. The low temporal resolution of the Cluster plasma parameters used in the study will inevitably lead to an experimental argument in favor of mirror-stability in such regions. The THEMIS spacecraft are able to provide an estimation of the threshold condition with a time resolution as low as 3 seconds. The typical duration of a magnetic hole is a few times longer than this period.

[3] The main aim of this paper is to determine if the condition for mirror instability is satisfied at the locality of the magnetic holes using high temporal resolution THEMIS data.

2. The Linear Growth of Mirror Waves

[4] The linear mirror wave is a purely non-propagating, growing mode [*Vedenov and Sagdeev*, 1958]. The instability growth rate γ in the limit of small transverse wave numbers can be recovered by expanding the general fully kinetic expression given by [*Pokhotelov et al.*, 2004]

$$\gamma = \frac{|k_\parallel| v_{T_\parallel}}{\pi^{\frac{1}{2}}} \frac{T_\parallel}{T_\perp}\left[K - \frac{3}{4}\frac{k_\perp^2\rho_i^2}{\beta_\perp} - \frac{k_\parallel^2}{k_\perp^2\beta_\perp}\left(1 + \frac{\beta_\perp - \beta_\parallel}{2}\right)\right], \quad (1)$$

where $k_{\parallel(\perp)}$ is the component of the wave vector parallel(perpendicular) to the ambient magnetic field $\mathbf{B}_0$, $v_{T\parallel(\perp)} = (2T_{\parallel(\perp)}/m)^{1/2}$ the parallel (perpendicular) ion thermal velocity, $T_{\parallel(\perp)}$ the parallel (perpendicular) ion temperature, m is the ion mass, $\rho_i = v_{T\perp}/\omega_{ci}$ the ion Larmor radius, $\omega_{ci} = eB_0/m$ the ion cyclotron frequency, e the charge of the electron, $\beta_{\parallel(\perp)}$the plasma beta, and $K = T_\perp/T_\parallel - 1 - \beta_\perp^{-1}$. We note that equation (1) is only valid for the marginal conditions when $K \ll 1$ and $A \equiv T_\perp/T_\parallel - 1 \simeq \beta_\perp^{-1}$ and thus the perpendicular plasma beta in equation (1) can be replaced by the inverse anisotropy for convenience.

[5] The maximum instability growth rate is attained when [cf. Pokhotelov et al. 2008]

$$(k_\perp\rho_i)^2_{\max} = \beta_\perp \frac{K}{3} \quad (2)$$

$$\left(k_\parallel\rho_i\right)^2_{\max} = \frac{\beta_\perp^2}{1 + \frac{1}{2}\left(\beta_\perp - \beta_\parallel\right)}\frac{K^2}{12} \quad (3)$$

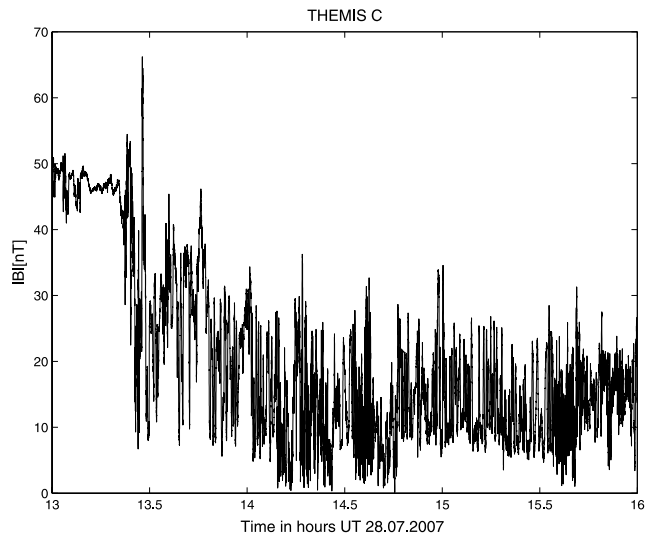

Figure 1. The magnitude of the magnetic field measured by THEMIS C during the period 1300–1600 UT on July 28th 2007.

and is given by

$$\gamma_{\max} = \frac{\omega_{ci}\beta_\perp K^2}{4\sqrt{3\pi}}\left(\frac{T_\parallel}{T_\perp}\right)^{3/2} \quad (4)$$

[6] From equations (3) and (4) it follows that $\gamma_{\max}/|k_\parallel|_{\max} v_{T\parallel} \propto K \ll 1$. The latter corresponds to the so-called "mirror approximation" [*Pokhotelov et al.*, 2002]. Furthermore, the parameter $(k_\perp\rho_i)^2_{\max}$ always remains smaller than unity. In order to prove this equation (2) may be re-arranged using the marginal stability condition $A \simeq \beta_\perp^{-1}$ such that

$$(k_\perp\rho_i)^2_{\max} = \frac{1}{3}\left(1 - \frac{1}{\beta_\perp A}\right) \quad (5)$$

[7] Since the onset of the instability corresponds to $\beta_\perp A > 1$, from equation (5) it follows that $(k_\perp\rho_i)^2_{\max} < 1/3$. This justifies our expansion in powers of small parameter $(k_\perp\rho_i)^2$.

3. Instrumentation and Data

[8] The data used in this paper come from the magnetometer [*Auster et al.*, 2008] and electrostatic analyzer (ESA) [*McFadden et al.*, 2008] instruments onboard the THEMIS satellites C and D [*Angelopoulos*, 2008]. During the time interval 1030–1530 UT on July 28th, 2007 the satellites operated in fast survey mode. In this mode, THEMIS provides magnetic field vectors with a time resolution of 0.25 Hz and is capable of measuring a full ion distribution in one spin i.e., 3 seconds. After 1530 UT THEMIS switched into slow survey mode. The magnitude of the magnetic field $|B|$ as observed by THEMIS C during the period of fast survey data is plotted in Figure 1. From Figure 1, it can be seen that THEMIS C exited the magnetosphere and entered the magnetosheath around 1320 UT, in the region of the nose of the magnetopause (10.9, −3.2, −3.2)Re (GSE). The spacecraft continued on the outbound leg of its orbit, eventually crossing the bow shock at around 1907 UT. During the period of interest, the separation vector from satellite C to D

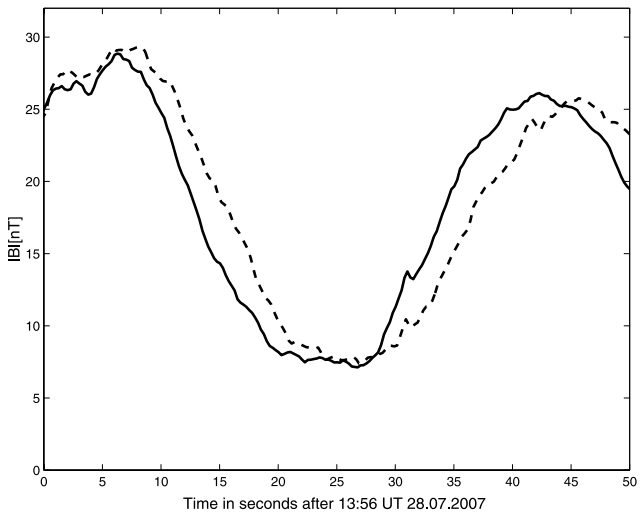

Figure 2. A comparison of measurements of the magnitude of the magnetic field measured by the spacecraft THEMIS C (solid) and D (dashed) showing examples of peak type mirror structures.

was of the order of (−122, 280, 101)km in the GSE frame, the total separation being 324 km.

4. Mirror Structures Observed by THEMIS C in the Magnetosheath

[9] During the initial part of the magnetosheath crossing, when spacecraft were close to the magnetopause, mirror structures were observed in the form of dips in the magnitude of the magnetic field. However, as the spacecraft traversed the magnetosheath, the nature of the mirror modes changes at approximately 1400 UT with a transition from dips to peaks. At this moment spacecraft were located approximately 0.5 Re upstream from the magnetopause. Such changes in the type of mirror structures observed have been reported a number of times previously [e.g., *Soucek et al.*, 2008]. This transition is associated with a change in the stability of the mirror wave. *Soucek et al.* [2008] concluded that the mirror dips are observed in a mirror stable plasma whilst the peaks are observed in a region of mirror unstable plasma. Some of the series of dips mirror mode structures are observed simultaneously by both the THEMIS C and D spacecraft. These simultaneous observations enable the determination their spatial scales. Figure 2 displays simultaneous measurements by THEMIS C and D spacecraft of a period when dip-type mirror structure were observed. The time delay Δt between observation allows the estimation the spatial scale $\lambda_\perp$ of these structures in the direction perpendicular to the magnetic field $\lambda_\perp = \frac{R_\perp T}{2\pi\Delta t}$, where T is apparent time period of the mirror structure in the spacecraft frame, and $R_\perp$ the separation of the spacecraft in the direction perpendicular to the magnetic field. For the mirror structure displayed in Figure 2 $\lambda_\perp \sim$ 205 km i.e., $\sim 10^1 \rho_i$. Figure 3a displays the modulus of magnetic field (black solid) density (grey) and the threshold K (asterisk) for 3 dip-type mirror structures observed by THEMIS D. K is scaled by factor 10. The dash-dotted line, indicating $K = 0$ line is added for convenience. It can clearly be seen that when the mirror structures are not observed $K < 0$ and that K is always positive when the dips are observed. The

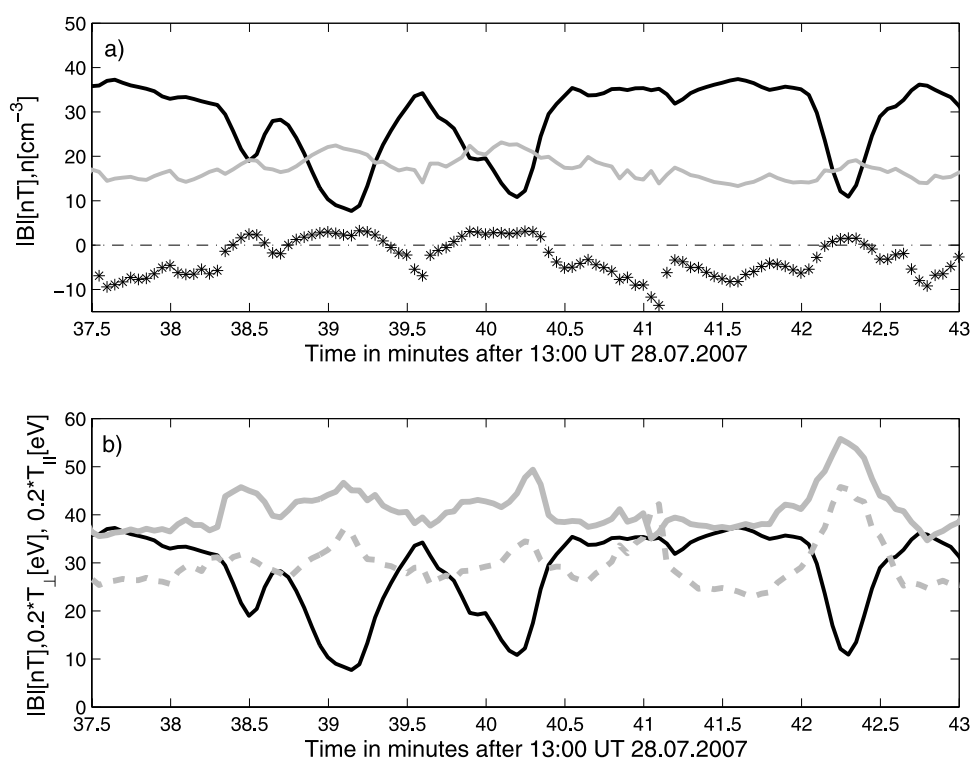

Figure 3. (a) Comparison of the magnitude of the magnetic field (black) and ion density (gray) for a series of magnetic dip-type structures. The asterisks show the value of the K, the threshold condition multiplied by a factor 10. (b) Comparison of the magnitude of the magnetic field (black solid) with changes observed in the parallel (gray, solid) and perpendicular (gray, dotted) ion temperatures (multiplied by a factor of 0.2).

modulus of the magnetic field (black solid line) together with the parallel $T_{\|}$ (solid gray) and perpendicular $T_{\perp}$ (dashed gray) ion temperatures for the same mirror structures are plotted in Figure 3b. As shown above, the scale size of the mirror waves are large enough in comparison with the Larmor radius for the drift approximation to be valid and the adiabatic invariant $v_{\perp}^2/B$ to be conserved. Therefore it is reasonable to assume that the decrease in the perpendicular ion temperature $T_{\perp}$ observed within the magnetic dips will be accompanied by a similar decrease of the magnetic field. However, Figure 3b shows that both the parallel and perpendicular temperatures are increasing simultaneously with the decrease of the field in the magnetic dips. Similar tendencies have been observed for other magnetic holes detected by the THEMIS C and D spacecraft during this and other crossings of the magnetosheath.

5. Discussion and Conclusions

[10] According to *Russell et al.* [2008] mirror wave are messengers from coronal heating processes that carry information about ion cyclotron waves in the corona. *Russell et al.* [2008] concluded that the mirror waves generated in the solar corona can survive in a mirror stable plasma long enough to reach a distance of 9 AU. The THEMIS results presented here show how these waves survive in the stable environment and support the conclusions of *Russell et al.* [2008]. Initially mirror waves would be generated as oscillatory structures. Such mirror structures are often observed in the magnetosheath downstream of the terrestrial bow shock where the temperature anisotropy is high [*Soucek et al.*, 2008]. The free energy stored in the temperature anisotropy provides conditions for the fast growth of mirror waves as has been demonstrated theoretically and investigated in many numerical simulations [*Pokhotelov et al.*, 2008; *Hellinger*, 2007]. Once grown to nonlinear amplitudes, the non-propagating mirror structures are convected away by the bulk plasma motion and eventually exit region in which they grew. If mirror structures are carried into a region where the threshold of mirror instability is not exceeded, small amplitude mirror waves would not be able affect the surrounding plasma and would decay with time. However, the fate of large amplitude structures is quite different. In the case of peak-type magnetic structures, the nonlinear oscillations lead to a local decrease in the effective β which results in a localized region of plasma that is more mirror stable than the surrounding plasma, leading to a greater damping of the structure. In contrast, for magnetic dip-type structures the amplitude of the magnetic field within the structure will decrease by a significant factor (5–7 times in Figures 2 and 3). Inside such structures that typically possess a spatial scale of a few ion Larmor radii the effective plasma β is higher than that of the surrounding plasma. If the depth of the magnetic hole is large enough the increase in β can lead to instability. Therefore, in the regions of nonlinear mirror waves that correspond to minima the interplay between the magnetic field and the non-resonant and resonant particles results in a region of mirror unstable plasma even when such a structure is surrounded by a mirror stable plasma. As the structure travels with the plasma bulk flow it carries with it its own habitat that it requires for its survival. *Pokhotelov et al.* [2008] suggested that the particle trapping processes are the key to the nonlinear dynamics of mirror structures. Figure 3 can be used as a justification for this model. The spatial scales of mirror structure are large enough for a drift approximation to be valid. In such a case the perpendicular velocity of an untrapped particle should decrease as it enters the mirror holes due to the conservation of the magnetic moment $\mu = v_{\perp}^2/|B|$. Therefore, it is reasonable to expect that the perpendicular temperature $T_{\perp}$ will decrease with the magnetic field decrease in the hole. However, the THEMIS data demonstrate that, in fact, the opposite appears to be true. The perpendicular temperature always has a local maximum that coincides with magnetic hole. A mirror wave that traps a significant quantity of ions as it is convected by the plasma flow can explain this increase in the perpendicular temperature.

[11] It is possible to summarize the results of the present paper as follows. It is not surprising that in regions in which magnetic hole type structures are scarce, the condition for the mirror instability threshold averaged over spatial intervals that greatly exceed the observed spatial size of any mirror structures is not satisfied because in any region in which the mirror instability threshold is exceeded mirror structures should grow. If the distance between mirror structures significantly exceeds the spatial scale of structure itself, the averaged condition for mirror instability should not be satisfied. The occurrence of large amplitude mirror holes result in a local increase of plasma β. Such an increase can lead to the local mirror instability threshold being exceeded, even when the magnetic hole is surrounded by a mirror stable plasma. In addition, the dynamics of changes in the perpendicular ion temperature indicates the importance of trapped particles for the dynamics of mirror wave.

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