Mirror Mode Structures in the Solar Wind: STEREO Observations

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Abstract. Mirror mode structures occur in the solar wind either as an isolated magnetic field depression or as trains of magnetic holes (or peaks). Some trains have long durations and have been named mirror mode storms [1]. In this work we investigate mirror mode structures at 1 AU using STEREO A and B high resolution data. Magnetic field data were scanned to search for magnetic holes and peaks in a relatively steady ambient solar wind. We found several examples of mirror mode structures present in the ambient solar wind and also associated with SIRs. In order to study mirror mode origin, we present a case study with mirror mode structures present in the leading edge of a SIR during almost 8 hours corresponding to mirror mode storms. We analyze mirror mode shape and duration as well as plasma and magnetic field conditions that occur in the region surrounding mirror mode storms.

Keywords: mirror mode, mirror waves, mirror instability, magnetic holes, magnetic peaks.
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INTRODUCTION

Before STEREO launch mirror mode waves had been found in the solar wind at various heliocentric distances either as isolated holes or trains of closely-spaced magnetic holes [2,3,4,5]. Recently, using STEREO high resolution data Russell et al. [1] reported some events of trains which persisted for hours and were refered to as "mirror mode storms". These waves were found in high β solar wind or downstream of weak interplanetary shocks. Figure 1 shows an example of a mirror mode storm event observed on July 10, 2007.

Here, we use STEREO data from 2007 and report an unusual event of several mirror mode storms observed during almost eight hours. These storms were found downstream of the forward shock of a stream interaction region (SIR), which turns out to be a very common region where mirror mode structures exist.

DATA AND METHOD

We use magnetic field and plasma data from the STEREO mission for the interval of February-July 2007. The sampling frequencies are 8 Hz for magnetic data and 1 sample per minute for plasma data. We scanned magnetic field data from STEREO A and B using 600 s windows making a visual inspection to select unambiguous events where local magnetic field depressions (magnetic holes) or magnetic field "humps" (peaks) were embedded in a relatively steady ambient magnetic field.

We investigate the occurrence and characteristics of magnetic holes or peaks present in the solar wind as *trains* or as the so called *mirror mode storms.*

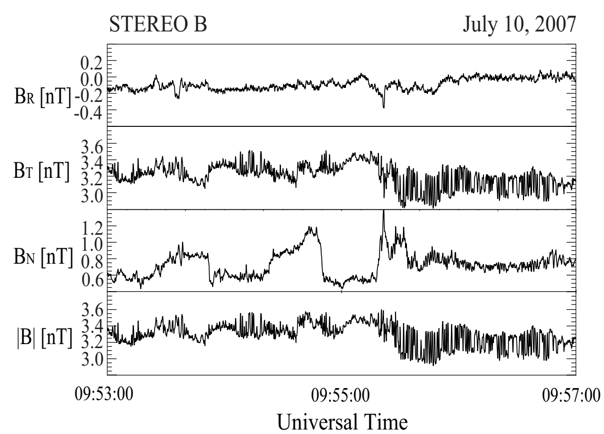

FIGURE 1. Magnetic field observations of a mirror mode storm observed downstream of a forward shock associated with a SIR (Stream Interaction Region).

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To identify trains of mirror mode waves we use Zhang et al. [5] criteria, which states that a train of mirror mode holes (or also peaks in this case) is defined if there is at least a second comparable magnetic hole (peak) in a 5 minute interval. On the other hand, a mirror mode storm will be defined as episodes of persistent mirror mode holes (peaks) which occur in intervals of at least 10 minutes as long as there are 2 dips or peaks in 40 s sliding windows. This last requirement guarantees the presence of a sufficient number of mirror mode elements within a short interval for an event to be considered a mirror mode storm. This number was obtained empirically after looking carefully at all the events studied from February-July 2007 and those reported in [1].

We found mirror mode waves (trains and storms) in 6 well-developed SIRs in both STEREO A and B. In some of these, mirror mode structures were present in the leading edge of the interaction region, namely in the downstream region very close to the forward shock. In some others, mirror mode waves were found inside the interaction region (not close to the shock) and also downstream of forward shocks of not fully developed SIRs. We also found a few examples of mirror mode storms being convected in the ambient solar wind.

In what follows we will study a remarkably long lasting event of mirror mode storms observed in the leading edge of a SIR observed on July 10, 2007.

Case study: July 10, 2007 mirror mode storm

Figure 2 shows a SIR from July 10, 2007 where mirror mode storms were present in the downstream region of the forward shock. This was a day full of mirror mode activity. The first storm appeared at 09:53, soon after the passage of the forward shock registered at 09:48. The occurrence of mirror mode structures did not cease until 17:30, providing us with a unique opportunity to study in more detail the evolution of the mirror mode structures during a very long lasting interval.

Figure 3 shows the evolution of the mirror mode structures in intervals of 40 seconds. At the very beginning of the event, near the shock, mirror mode waves are mainly "peaks" (top of figure). Also, mirror mode structures tend to be closer between them. As time passes the structures turn into holes which by the end of the event are deeper, wider and more separated (see intervals F and G). This supports Russell's et al. [1] idea that perhaps there is an evolutionary path between mirror mode waves formed near interplanetary shocks as "peaks" and then observed as isolated holes in the solar wind as they are convected by the flow. Such behaviour is also consistent with observations in planetary magnetosheaths [6,7] where peaks have been found in the middle magnetosheath (closer to the shock) and most holes near the magnetopause.

To study in detail the development in the solar wind of mirror mode storms throughout the day of July 10 we plot in Fig. 4a and 4b time series (magnetic field and plasma parameters) from 08:30 to 17:30 UT. Shaded regions correspond to the A-G events shown in Fig. 3. We also summarize in Table 1 average values of magnetic field strength and plasma quantities from ambient solar wind (before the shock) and events A-G.

Figure 4a shows that before the mirror mode onset (interval A) there is an enhancement in all the parameters, as expected after a shock. Five minutes after the passage of the shock mirror mode structures begin to be observed as "peaks" (see Fig. 3) in regions A and B. Inside these events average $\beta > 6$. Later, in events C and D the number of mirror mode elements decreases substantially and magnetic field and plasma parameters remain almost constant. Then mirror mode structures are observed again but this time as holes.

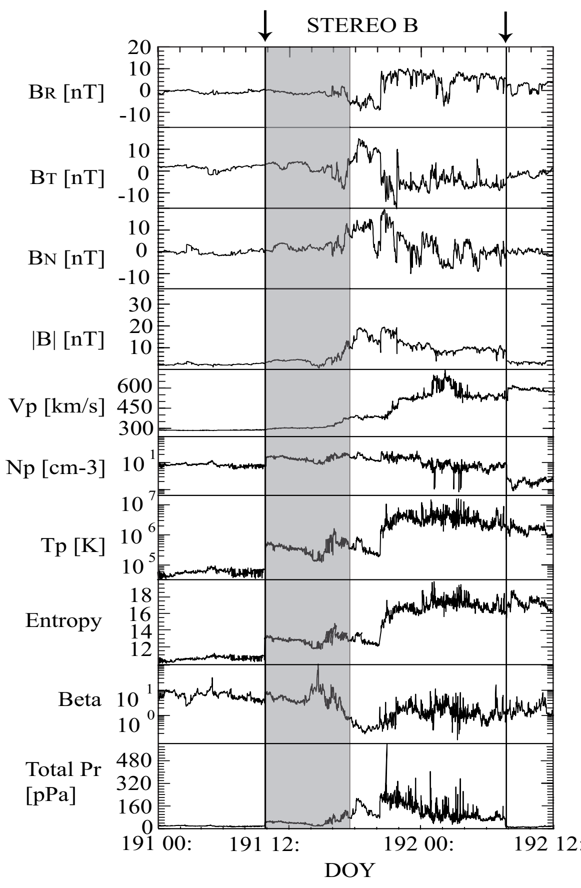

FIGURE 2. SIR observed on July 10, 2007 (edges of SIR indicated with arrows). Mirror mode storms (shaded area) were observed downstream of the forward shock.

TABLE 1. Average values for ambient solar wind parameters and intervals shown in Fig. 4

Event	Ambient	A	B	C	D	E	F	G
B(nT)	2.5	2.9	3.1	4.1	1.2	2.1	4.3	4.3
Velocity (km/s)	280	295.2	299.4	303.3	304.6	310	316.7	361.3
Density (cm^{-3})	8	16	16.4	16.1	11	10.8	13.8	18.5
Temperature (K)	$0.5x10^4$	4.3×10^4	4.5×10^4	3.8×10^4	1.9×10^4	2.2×10^4	4.4×10^4	5.2×10^4
β	5	9.2	6.8	6.1	9.6	18.3	7.3	3.6

Finally the number of holes starts to increase and before deeper holes appear in E, F and G, sudden increases in plasma parameters are observed (see arrows in Fig. 4b indicating such sudden increases).

As seen in Fig. 4b, just before event E starts, plasma density changes from 8 up to 12 cm^{-3}, in region F from 12 to 16 cm^{-3} and in region G from 18 to 23 cm^{-3} approximately. The plasma temperature rises before event E from $1x10^4$ to $3x10^4$ K, before F from $3x10^4$ to $7x10^4$ K and before G from $1x10^5$ to $1.5 x10^5$. The β parameter shows the same behaviour of sudden increases only before the mirror mode storm in E, reaching a maximum value of 130 approximately.

Inside the regions where mirror storms are embedded in E, F and G (see darker shaded areas in Fig. 4b), density and temperature continue rising up to average values of 18.5 cm^{-3} and $5.2x10^4$ K respectively (see Table 1). In contrast, the plasma β does not follow this general trend. Inside events E and F (where mirror mode holes are observed) average β values are 18.3 and 7.3 respectively. The striking observation comes by the end of the time series in Fig. 4b inside the region where deeper holes are observed (i.e event G). Here the plasma β displays values even smaller than the ambient solar wind, although no smaller than 1.5.

Previous observational studies of the Earth's magnetosheath [6] and Jupiter's magnetosheath [7] have shown that mirror mode holes can exist in plasmas with relatively small β and large anisotropy, whereas mirror mode peaks grow where β displays larger values and the anisotropy is moderate. What is more, the combined view of observations and models [8] for planetary magnetosheaths has lead to the suggestion that the threshold condition for the linear mirror instability (which is dependent upon β and temperature anisotropy) is the key to understand the evolution of mirror mode structures and their shape [6]. According to this, peaks appear only in mirror unstable plasmas (i.e in magnetosheaths near planetary shocks) while holes may exist in a large domain of plasma conditions, even in mirror stable plasma.

SUMMARY

Before the launch of STEREO, mirror mode structures in the solar wind were reported as isolated holes or trains of closely-spaced depressions in the magnetic field. Recently, high resolution data from STEREO have revealed that mirror mode structures in the solar wind are more complex than we had ever thought. They can occur not only as holes but as peaks or "square shapes" and can be observed during long periods as "mirror mode storms" [1]. We have found that mirror mode storms are frequently associated with SIRs. They can occur in the leading edge of the SIR (downstream of the shock) and also inside the interaction region. Mirror mode storms may be found in the ambient solar wind as well. We studied plasma and magnetic field properties inside and surrounding

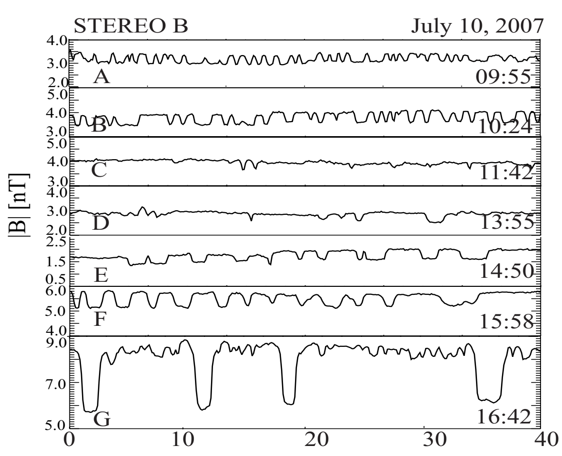

FIGURE 3. Forty seconds segments of B from 10 July 2007 showing a mirror mode storm. The starting time (HH:MM) of each segment is indicated on the right hand side.

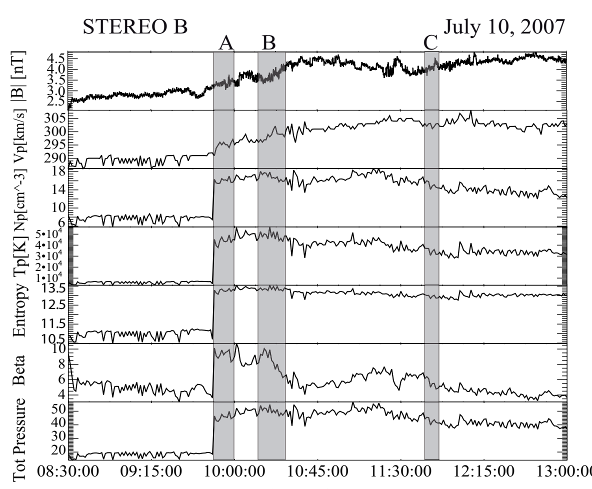

FIGURE 4a. Plasma and magnetic field properties near and during the intervals where mirror modes storms are present (dark shaded areas).

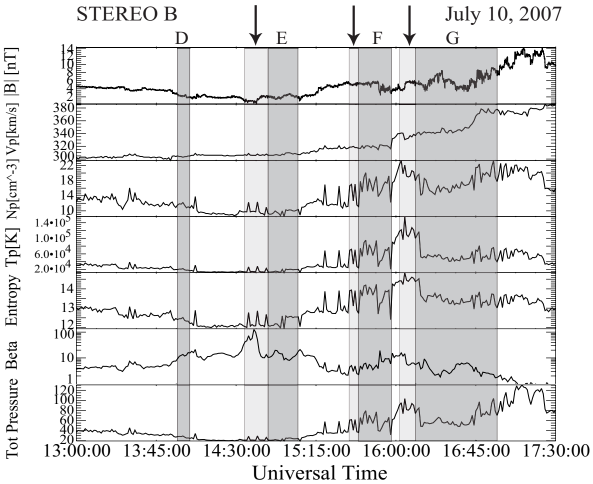

FIGURE 4b. Same as in Fig. 4a except for regions marked with an arrow in E F and G which indicate plasma conditions before the onset of mirror mode structures.

the mirror mode structures and reported here one exceptional event of long lasting mirror mode storms associated with the leading edge (downstream of the forward shock) of a SIR. We can summarize our findings as follows:

1. Mirror mode storms are frequently observed first as trains of "peaks" (near the forward shock) and then as trains of "holes" (far from shock).

2. It is observed that before the mirror mode onset plasma parameters show sudden increases. In these regions the plasma β increases 2 orders of magnitude reaching values between 10 and 130. Proton temperature is increased by a factor of 2 reaching values between $3x10^4$ and $2x10^5$ K and plasma density is also enhanced to values between 12 and 20 cm^{-3}.

3. While peaks are observed inside intervals related to higher β plasma conditions than ambient solar wind (near the forward shock), holes are observed in different regimes of β, even inside regions where β is smaller than the ambient solar wind value.

The transition from peaks near the forward shock of SIRs to holes far from shock may be interpreted in terms of plasma instability, as suggested in previous works of planetary magnetosheaths [6 and references therein]. Linear kinetic theory predicts that the combination of a high plasma β plus temperature anisotropies due to nonuniform plasma shock heating can make the plasma unstable to the mirror mode instability and explain the growth of mirror mode structures observed in the downstream region. We have found mirror mode storms (holes and peaks) in plasmas with high β between 6.1 and 18.3. However, there are also some mirror mode storms present as holes that can "survive" in regions where β values are not high, i.e β~1.5, in both plasmas related to SIRs and in ambient solar wind. Unfortunately, STEREO has not provided temperature anisotropy data yet, but we expect to find large anisotropies near the forward shock due to shock heating processes and smaller values far from shock since enhanced wave particle interactions lead to proton isotropization.

We propose the following scenario for our observations: near the forward shock the plasma has experienced shock heating making the plasma mirror unstable. Thus, just downstream from the shock, temperature anisotropy and β are large which favours the occurrence of peaks. Far from shock the plasma becomes more isotropic and β may also decrease, therefore the plasma turns mirror stable accompanied by a decay in peaks and an increment in holes, since these latter can "survive" different plasma conditions. This explains the fact that holes can be found in plasmas with smaller values of β than peaks, like those shown in Fig. 3. To sum up, it is the combination of β plus temperature anisotropies what makes the plasma stable or unstable to the mirror mode instability and determines the shape of mirror mode structures.

For future work we will calculate the growth of kinetic instabilities due to temperature anisotropies at high β to explain the occurrence of mirror mode structures in the solar wind. More simulation work is required to understand the overall 3D configuration of mirror mode structures, which is still largely undetermined and remains a matter of investigation.

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