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Observational support for the electron mirror mode: AMPTE-IRM and Equator-S measurements in the magnetosheath

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Abstract. Based on AMPTE-IRM and Equator-S observations in the magnetosheath near the dayside magnetopause we provide observational support for a recent theory by Noreen et al. (2017) of the contribution of the electron mirror instability to the evolution of mirror modes in the high-temperature anisotropic collisionless plasma of the magnetosheath.

Keywords. Mirror modes, Electron mirror mode, Magnetosheath turbulence

1 Introduction

Magnetic mirror mode observations in the magnetosheath as well as in the magnetotail of Earth's magnetosphere and also elsewhere have been ubiquitous in the past four decades (see Tsurutani et al., 2011; Sulem, 2011, for reviews on observation and theory, respectively). They were, however, restricted to the ion mirror mode and the detection of electron-cyclotron waves (lion roars) which propagate in the whistler band inside the magnetic mirror configuration and are caused by trapped electrons (cf., e.g., Baumjohann et al., 1999; Maksimovic et al., 2001; Remya et al., 2014). These observations confirmed their theoretical prediction based on fluid (cf., e.g., Chandrasekhar et al., 1958; Chandrasekhar, 1961; Treumann and Baumjohann, 1997; Baumjohann and Treumann, 2012) and the substantially more elaborated kinetic theory (cf., Pokhotelov et al., 2002, 2004, and further references in Sulem, 2011).

Recently this theory has been extended to the inclusion of the effect of anisotropic electrons on the evolution of mirror modes (Noreen et al., 2017) in the linear and quasi-linear regimes. Though in principle simple matter, the interesting finding was that the electrons do substantially contribute to the evolution of mirror modes and quasilinear saturation though in different wavenumber and frequency/growth rate regimes. This leads immediately to the question of observation of such effects in the mirror modes. Here we demonstrate that, based on three decades old AMPTE-IRM observations in the magnetosheath near the dayside magnetopause and two decades old Eq-S magnetic high resolution observations in the equatorial magnetosheath, both modes have indeed already been observed.

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2 Observations

Figure 1 shows a typical sequence of magnetosheath mirror modes lasting longer than six minutes during an AMPTE-IRM passage on September 21, 1984. The lower panel shows variation of the magnitude of the magnetic field that is caused by the (ion) mirror mode with amplitude $|\delta B| \sim 0.5|B|$. The upper panel is the wave electric power spectrogram. The wavy white line is the electron cyclotron frequency f_{ce} which maps the magnetic field from the lower panel into the frequency domain. Lion roars emitted in the central mirror mode minima are indicated for two cases. As was shown from high resolution Equator-S spacecraft measurements a decade later (Baumjohann et al., 1999) these emissions are in the whistler band propagating in wave packets nearly parallel to the magnetic field with central frequency roughly $f_{lr} \sim 0.1 f_{ce}$ of the local central cyclotron frequency. The origin of the other sporadic intense emissions centred around $f \sim$ 0.5-0.7 kHz remained unclear. They are not related to the mirror mode minima. They rather occur at the mirror mode flanks, being of more broadband nature, more temporarily irregular and of higher frequency. In addition there are irregular high frequency broadband electric signals above f_{ce} reaching up to the local plasma frequency at $f_e \sim$ 60-70 kHz. Their spiky broadband nature being independent of the presence of the cyclotron frequency suggests that they are related to narrow structures or boundaries of which such broadband Fourier spectra are typical. The broad unstructured (green) quasi-stationary noise below roughly 2 kHz propagates in the electrostatic ion-acoustic band and is of little interest here.

We will argue that the broadband sporadic nature of the unidentified emissions, their relation to the flanks of the ion mirror mode, and intensification below the local cyclotron frequency suggests that they are the signatures of electron mirror mode structures which are superimposed on the ion mirror mode which dominates the gross behaviour of the magnetic field.

For this purpose we refer to a rare observation by the Eq-S spacecraft which is reproduced in Figure 2. Unfortunately, as had already been noted (Baumjohann et al., 1999) no plasma measurements were available due to failure of the instrument. The figure shows a high resolution record of the magnetic field magnitude from the data pool of Eq-S (used in Baumjohann et al., 1999). Two mirror mode cycles are shown. One sees the general evolution of the magnetic field which is reflected in the slight asymmetries of the structures which pass over the spacecraft. These might be caused by evolution of the mode or also by crossing the mirror mode under an angle. The maximum of the magnetic field in this case is $\sim$ 30 nT with a $\sim 50\%$ amplitude oscillation. The small amplitude fluctuations of the field in the field minima belong to the Lion roars mentioned above and have been investigated in detail (Baumjohann et al., 1999). In the left hand field minimum the local magnetic maximum can be recognised to which the above paper refers as an unexplained structure.

The interesting feature in this high-resolution recording of the magnetic field are the tooth-like oscillation of the field in the flanks, in the maxima and also in the minima. In this respect the high resolution magnetic field in this figure is quite different from the apparent smooth course of the mirror field in the AMPTE-IRM observations of Fig. 1.

In order to infer about the nature of these oscillations we may refer to the period of the (ion) mirror mode. This can be read from the figure to be roughly $\tau_{im} \sim 30$ s, corresponding to a frequency of $f_{im} \sim 0.03$ Hz. The tooth-like oscillations, for instance at the first steep increase of the magnetic field, have a time period of $\tau \sim 2-4$ s (or frequency $f \sim 0.3$ Hz), roughly a factor of ten shorter than the ion-mirror mode. In addition to their steep magnetic boundaries, these structures also exhibit

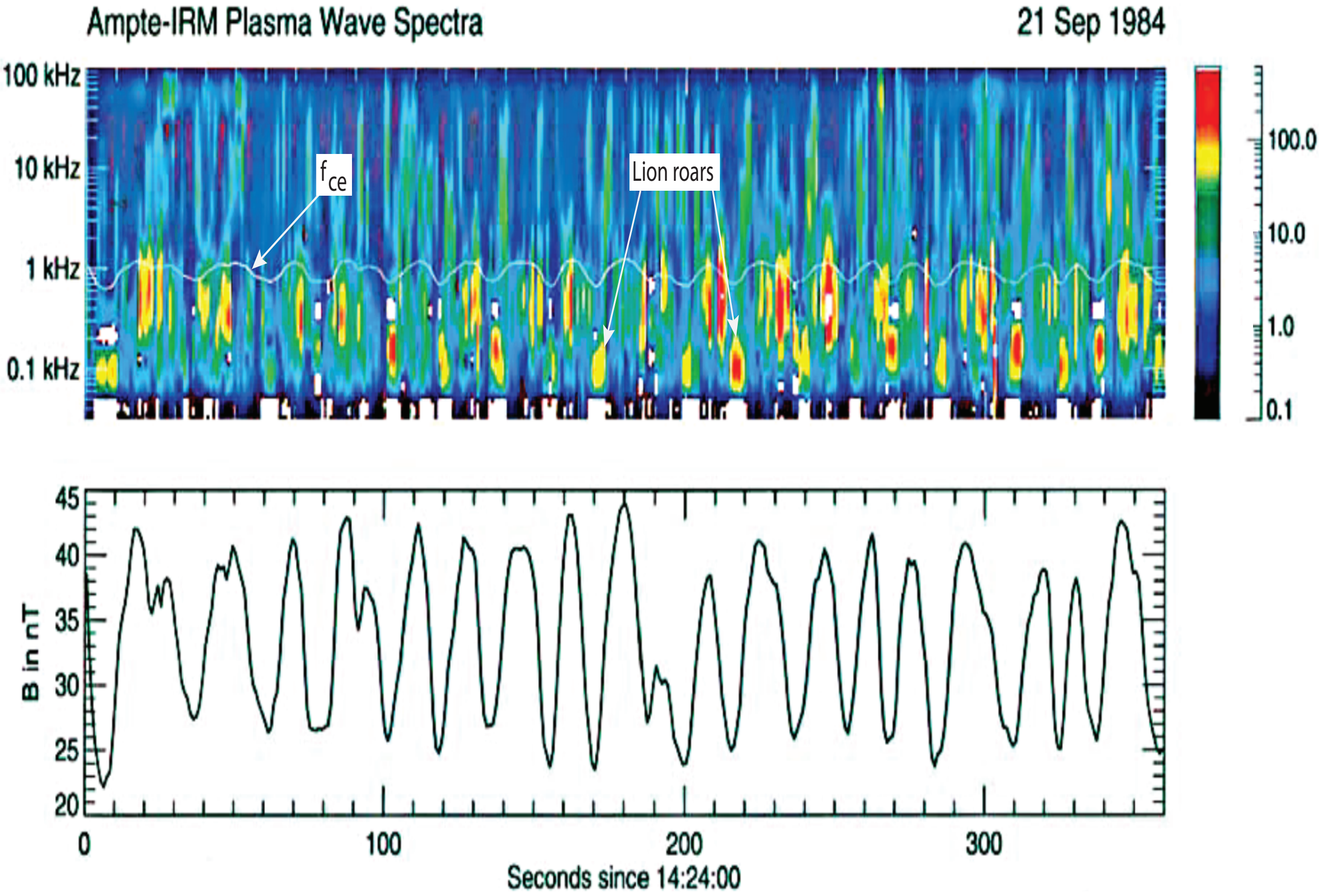

Figure 1. AMPTE-IRM observations of mirror modes in the magnetosheath and related plasma wave power spectra (see the colour bar on the right for relative log-scale intensities). Indicated are the electron cyclotron frequency f_{ce}, and Lion roar emissions in the mirror mode minima at frequency $f_{lr} \sim 0.1 f_{ce}$ (after Treumann et al., 2004).

superimposed small frequency oscillations which are also present in the modulated maxima of the mirror mode. Since the latter belong to magnetic fluctuations it is reasonable to assume that they are simply a different kind of Lion roars caused by electrons trapped in the local minima of the higher frequency-shorter wavelength modulations. Thus their centre frequency should be higher than the Lion roar frequency in the ion-mode minima. This suggests identification with the higher frequency spectral features observed by AMPTE-IRM, while the weak broadband features in the wave spectra may be related to the steep magnetic and plasma (pressure) boundaries of the modulations.

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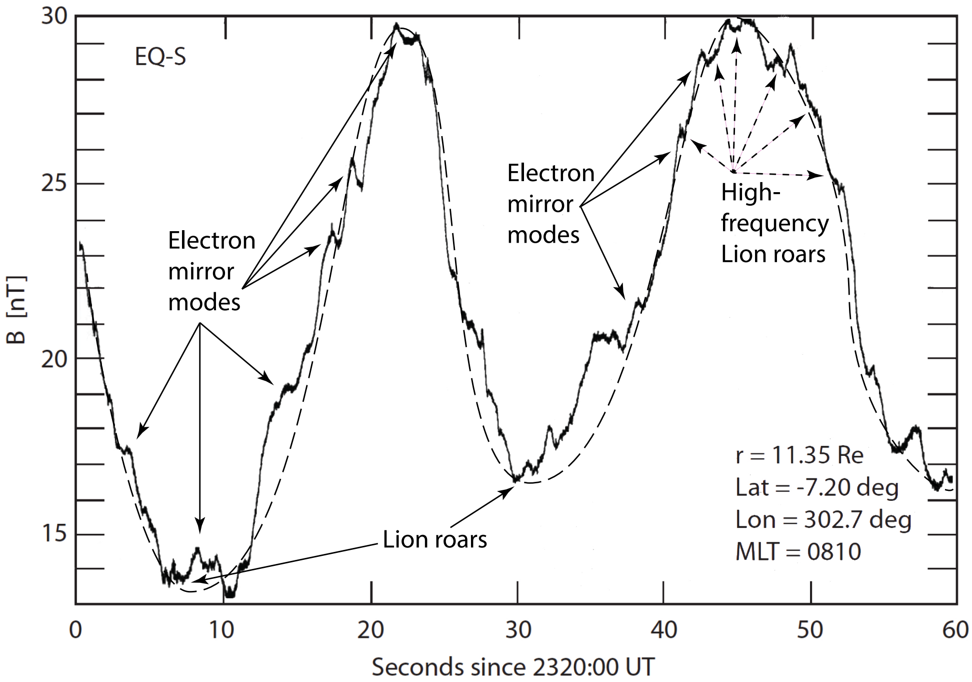

Figure 2. High resolution Eq-S observations of mirror modes in the magnetosheath near the magnetopause. The dashed line is a quasi-sinusoidal approximation to the ion mirror mode structure. Asymmetries are presumably caused by the obliqueness of the ion mirror mode structure in combination with the plasma flow which transports them to pass over the spacecraft. The strong modulation of their shapes on the smaller scale is produced by the superimposed small-scale electron mirror mode structure on the ion mirror mode. Signatures of Lion roars are found in the ion mirror minima. High-frequency Lion roars concentrate in the minima of the electron mirrors.

3 Electron mirror mode

If this is the case then it is suggestive to identify the small amplitude modulations in the magnetic field seen by Eq-S and in the wave spectra by AMPTE-IRM with the electron mirror mode which was theoretically predicted (Noreen et al., 2017). These authors put emphasis on the quasilinear evolution of the pure electron (ion) and mixed (electron-ion) mirror modes to numerically show for a number of cases how the normalised magnetic and plasma energy densities evolve and saturate. For our purposes it suffices to consider the mixed linear state, because it is clear from the data in Fig. 2 and as a consequence also in the spectrum of Fig. 1 that the dominant magnetic (and also plasma) structure is the ion mirror mode while the electron mirror mode just produces some modification. Clearly the ion mirror mode is a large-scale perturbation on which the quasilinear contribution of the electron mirror mode does not change very much.

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For our purposes we need only the simplified purely growing linear growth rate (normalised to the ion-cyclotron frequency $\omega_{ci} = eB/m_i$) for small ion and electron arguments

$$\gamma(\boldsymbol{k}) \approx \frac{k_\| \lambda_i}{A_i + 1}\sqrt{\frac{\beta_{\|i}}{\pi}}\left[A_i + \frac{T_{e\perp}}{T_{i\perp}}A_e - \frac{k^2}{k_\perp^2 \beta_{i\perp}}\right] \tag{1}$$

with $\lambda_i = c/\omega_i$ the ion inertial length, $\omega_i^2 = e^2N/\epsilon_0 m_i$ square of ion plasma frequency, $A_j = (T_\perp/T_\|)_j - 1 > 0$ the temperature anisotropy of species $j = i, e$, and $\beta_{\|i} = 2\mu_0 N T_{i\|}/B^2$ the ratio of parallel ion thermal and magnetic energy densities (cf., Noreen et al., 2017, Eq. 4, corrected for typos). Wave growth occurs for positive bracket which provides angular dependent thresholds. The threshold condition can be written in terms of the magnetic field as

$$B < B_{crit} \approx \sqrt{2\mu_0 N T_{i\perp}}\left(A_i + \frac{T_{e\perp}}{T_{i\perp}}A_e\right)^{\frac{1}{2}}\left|\sin\theta\right| \tag{2}$$

where $\theta = \sin^{-1}(k_\perp/k)$, and the approximate sign refers to the simplifications made in writing the simplified dispersion relation. Thus once the local magnetic field drops below this threshold one or both of the mirror instabilities will necessarily set on. Such a critical value B_{crit} exists for all combinations of anisotropies which leave the sum under the root positive. It has a deep physical meaning (Treumann et al., 2004).

It is clear from these expressions that the two modes grow in separate regions of wavenumber space $k_\|, k_\perp$, where the indices refer to the directions parallel and perpendicular to the local magnetic field, i.e. in the ion mirror mode to the average ambient magnetic field which is modulated by the mirror mode, in the electron case the local magnetic field at the location where the electron mirror bubble evolves (Noreen et al., 2017, see their Fig. 1). This main (and well expected) effect in the combined electron-ion growth rate found by numerically solving the non-simplified growth rate (Noreen et al., 2017, their Eq. 4) is that, because of the vastly different scales of electrons and protons, the growth rate exhibits two separate branches. Since in the linear state the different modes extract their energy solely from the component of particles to which they belong, the two modes grow practically separately. Only in the quasilinear state an exchange in energy takes place (as shown by Noreen et al., 2017).

In absolute numbers the electron mirror growth rate (measured in ion cyclotron frequencies) is about an order of magnitude larger than that of the ion mirror mode. It grows faster and, as a consequence, saturates readily, such that one expects it to be of comparably small final amplitude. The ion mirror mode growth rate maximises at $k_{\|i} \approx k_{\perp i}$, at about an angle of $\sim 45^\circ$ to the magnetic field, while the electron mirror mode is nearly perpendicular $k_{\|e} \approx 0.1 k_{\perp e}$. On the other hand, the maximum unstable parallel wavelengths are comparable, $k_{\|e} \approx 3k_{\|i}$, while the maximum unstable perpendicular wavelengths are different: $k_{\perp e}/k_{\perp i} \approx 20 - 30$ for the parameters investigated (Noreen et al., 2017). The electron mirror mode structure is elongated essentially parallel to the local field, while the ion mirror mode is oblique to the ambient field. Whereas the ion mirror mode tends to form large magnetic bubbles, the electron mirror mode forms narrow long bottles on the structure given by the ion mirror mode. We may assume that this behaviour will not be very different for other parameter choices than those used in the numerical calculation, as it is just what one would expect: the electron mirror mode somewhat shorter in parallel wavelengths and substantially shorter in perpendicular wavelengths than the ion mirror mode, an effect of the vastly different gyroradii.

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4 Application and discussion

With this information at hand we can consult the high resolution Eq-S observations in Fig. 2. This figure suggests that Eq-S was crossed by the chain of mirror structures almost in the perpendicular direction. Comparing the times of crossing the large-scale ion mirror mode and the well expressed small scale structure on the flank of the first rising boundary we infer that the ratio of wavelengths between the long and short structures is of the order of roughly a factor of ~ 10. Though this is not exactly the above value for this ratio in the perpendicular direction, it is pretty close to the expectation that the small scale structure is caused by the electron component thus representing the electron mirror mode.

There are a number of shorter structures of smaller amplitudes visible the use of which would come closer to the canonical scales obtained from the numerical calculation of the maximum growth rates (Noreen et al., 2017). However there are many reasons for staying with this result. The first would be the choice of the parameters for the linear calculation. Another is that even for those parameters the spread of the domain of maximum growth of both the ion and electron mirror modes (cf. Fig.1 in Noreen et al., 2017) is sufficiently large for fitting the measurements. We may apply the half-maximum condition for exponential growth. Then the wave power is one fourth of its value at maximum growth for wave numbers $k_\perp$ with growth rate $\gamma(k_\perp) \sim 0.3\gamma_{max}$. Inspection of this figure shows that this condition implies a spread in $k_\perp$ for the electron mode of $\Delta k_\perp \lambda_i \sim 5$, large enough for covering a broad interval of electron mirror wavelengths. Finally, just to mention it, it is not known from the observations, in which direction precisely the electron mirror mode would propagate relative to the ion mirror mode. Hence, the above conclusion, though still imprecise, should suffice as evidence for the observation of both electron and ion mirror modes in the magnetosheath by Eq-S acting simultaneously in tandem. Unfortunately, as noted above, no plasma observations were available such that we are not in the position to provide a more sophisticated investigation of this very interesting case.

Accepting that Eq-S has indeed observed both modes in the magnetosheath, reference to Fig. 2 further suggests that, as suspected, the higher frequency unidentified waves in Fig. 1 represent the equivalent to lion roars in the ion mirror mode though now in the electron mirror mode. Indeed, the perpendicular extension of an electron mirror mode though being much less than the ion inertial length $\lambda_i = c/\omega_i$ is, for a magnetic field of the order of $B \approx 25$ nT as in the measurements of Eq-S, still much larger than the electron gyroradius. This is also a general condition for the electron mirror mode to exist and grow. Thus electrons trapped inside the electron mirror structure will by the same reasoning (cf., e.g., Baumjohann et al., 1999, and others) be capable of exciting the whistler instability and thus produce high frequency lion roars below the local electron cyclotron frequency which in this case would be around $f \sim 0.5 - 0.7$ kHz which is in reasonable agreement with the majority of high intensity emissions below the local electron cyclotron frequency in Fig. 1 which are found to coincide with the walls and maxima of the ion mirror structures, and in some cases evolve even on top of the maxima (see also the cases indicated in Fig. 2) in the magnetic field strength.

Hence the higher frequency waves related to the mirror structures are presumably caused by anisotropic electrons trapped in electron mirror structures which grow on the background magnetic field and plasma structure of the ion mirror mode. Considering that mirror modes trap electrons and that there is plenty of reason for the trapped electrons to evolve temperature anisotropies, this is quite a natural conclusion. The weak broadband electric emissions exceeding the ambient cyclotron frequency and being irregularly related to the ion mirror structures then probably result from the steep plasma boundaries of the electron mirror mode structures, their trapped electron component which is responsible for the pressure balance, when traversing the spacecraft at the relatively high flow speeds in the magnetosheath.

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Data availability. No data sets were used in this article.

Competing interests. The authors declare that they have no conflict of interest.

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