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Key Points:

- An advanced numerical solver named DSHARK is used to resolve the linear dispersion for an arbitrary propagation in bi-Kappa distributed electron-proton plasmas
- Anisotropic electrons and their suprathermal populations stimulate the mirror instability in planetary magnetosheaths
- Suprathermals play a major role, extending the dominance regime of mirror instability

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Stimulated Mirror Instability From the Interplay of Anisotropic Protons and Electrons, and their Suprathermal Populations

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Abstract Mirror instability driven by the temperature anisotropy of protons can offer a plausible explanation for the mirror-like fluctuations observed in planetary magnetosheaths. In the present paper we invoke a realistic kinetic approach which can reproduce nonthermal features of plasma particles reported by the observations, i.e., temperature anisotropies and suprathermal populations. Seeking accuracy, a numerical analysis is performed using an advanced code named DSHARK, recently proposed to resolve the linear dispersion and stability for an arbitrary propagation in bi-Kappa distributed electron-proton plasmas. The stimulating effect of the anisotropic bi-Maxwellian electrons reported in Remya et al. (2013, <https://doi.org/10.1002/jgra.50091>) is markedly enhanced in the presence of suprathermal electrons described by the bi-Kappa distribution functions. The influence of suprathermal protons is more temperate, but overall, present results demonstrate that these sources of free energy provide natural conditions for a stimulated mirror instability, more efficient than predicted before and capable to compete with other instabilities (e.g., the electromagnetic ion-cyclotron instability) and mechanisms of relaxation.

1. Introduction

The so-called mirror unstable modes have been predicted to develop in magnetized plasmas with a pressure anisotropy $\beta_{\perp} > \beta_{\parallel}$, where the plasma parameter β is given by the ratio of plasma and magnetic field pressures, and $\perp, \parallel$ denote directions relative to the magnetic field (Chandrasekhar et al., 1958; Hasegawa, 1969; Tajiri, 1967). Resonant protons with low velocities parallel to the background magnetic field contribute to the growth of the instability (Southwood & Kivelson, 1993), and the simulations suggest that heavier ions, although a minor ingredient, may change the hierarchy of the instabilities, inhibiting the electromagnetic ion-cyclotron instability (EMIC) and implicitly favoring the mirror instability to develop (Price et al., 1986). More recently, Remya et al. (2013) have confirmed that in the absence of heavier ions the dominance regime of mirror is conditioned by very high proton beta values $\beta_p \geq 10$, while for a 4% presence of heavier ions this condition reduces to $\beta_p \geq 4$. For anisotropic electrons with $A_e > 1.8$ and 1% heavier ions the beta condition drops to $\beta_p \geq 0.5$. Mirror instability saturates by reducing the anisotropy of protons (McKean et al., 1993), and in the nonlinear phase the dominance against EMIC (which may dissipate quickly, see Gary, 1992) becomes more generalized (Shoji et al., 2009; Riquelme et al., 2015).

Apparently, the observations support the existence of mirror modes in different space plasma environments, like, terrestrial and other planetary magnetosheaths (Erds & Balogh, 1996; Hasegawa & Tsurutani, 2011; Narita et al., 2016; Tsurutani et al., 1982; Volwerk et al., 2008, 2016), cometary environments (Glassmeier et al., 1993; Russell et al., 1987; Tsurutani et al., 1999), the solar wind (Liu et al., 2006; Russell et al., 2009; Tsurutani et al., 1992) and the heliosheath (Tsurutani, Echer, et al., 2011), and even at sites of magnetic reconnection (Vörös, 2011). However, Tsurutani, Lakhina, et al. (2011) have shown that most of the traces reported in interplanetary space may actually be magnetic decreases of the ambient field, while mirror mode instabilities remain a major feature of planetary magnetosheaths and are only rarely seen in interplanetary space or at comets. In the magnetosheath the source of free energy for the observed mirror modes is the pressure or temperature anisotropy ($T_{\perp} > T_{\parallel}$) of protons generated by the compression in quasi-perpendicular bow shock and draping of magnetic field lines. These conditions are less specific for the interplanetary space explaining the more reduced probability to find these modes (Smith & Tsurutani, 1976; Tsurutani et al., 1982).

To understand the origin and implications of the mirror fluctuations in collisionless plasmas from space, for example, terrestrial and planetary magnetospheres, a kinetic approach is vital and requires a realistic characterization of particle distributions in accord with the observations. The main constituents of these hot and dilute plasmas are the electrons and protons, which exhibit nonthermal features, with anisotropic velocity distributions (e.g., temperature anisotropies, drifts, and beams) (Anderson & Fuselier, 1993; Samsonov et al., 2007; Soucek & Escoubet, 2011; Tsurutani et al., 1982), as well as suprathermal populations which enhance the high-energy tails of the distributions as additional sources of free energy (Formisano et al., 1973; Gosling et al., 1989; Lazar et al., 2012; Masood & Schwartz, 2008; Pierrard & Lazar, 2010). The thermal spread of electrons can have an inhibiting effect on mirror modes (Pantellini & Schwartz, 1995), but their instability may be substantially stimulated by the anisotropic electrons with $A_e = T_{e,\perp}/T_{e,\parallel} > 1$ (Pokhotelov et al., 2000; Remya et al., 2013). Moreover, mirror growth rates are enhanced (and thresholds are lowered) in the presence of suprathermal protons (Leubner & Schupfer, 2000, 2001) which are well reproduced by the generalized Kappa power laws (Pierrard & Lazar, 2010; Lazar et al., 2012). The influence of suprathermal electrons has been studied in combination with the effects of a loss cone in the distribution, aiming to provide a generalized criterion for the mirror instability (Pokhotelov et al., 2002). Suprathermal electrons have the same stimulating effect, enhancing the instability growth rates and lowering the anisotropy thresholds. However, all these results provide only a partial picture restricted to low frequencies (i.e., $\omega \ll \Omega_i$, where Ω_i is the ion gyrofrequency) or to a particular class of distribution functions (i.e., $F(W, \mu) = f(W)g(\mu)$, where W and μ denote the particle energy and magnetic moment, respectively), which does not include the family of Kappa power laws. On the other hand, the parametrization invoked was not necessarily relevant for the magnetosheath conditions, where the activity of mirror modes is most evident.

A comprehensive description of mirror modes has been achieved within numerical solvers, for example, WHAMP (Waves in Homogeneous Anisotropic Multicomponent Magnetized Plasma), (Remya et al., 2013), quasi-linear/nonlinear formalisms (Noreen et al., 2017; Yoon & Seough, 2012), and numerical simulations (Ahmadi et al., 2016; Price et al., 1986; Shoji et al., 2009) developed for standard bi-Maxwellian plasmas. From a contrasting quasi-linear analysis the long-term evolutions of mirror and EMIC instabilities appear to be consistent with the linear predictions, showing a predominance of EMIC for low beta plasmas and a more efficient mirror for high beta regimes (Yoon & Seough, 2012). However, the effects of anisotropic electrons have determined some controversial issues (Ahmadi et al., 2017; Remya et al., 2017) on theoretical predictions, which appear to be only partially confirmed by the simulations, identifying the whistler (electromagnetic electron cyclotron) instability developing faster and relaxing the highly anisotropic electrons with $A_e = T_{e,\perp}/T_{e,\parallel} > 1$. Intense packets of whistler waves (also known as lion roars) are often observed in the magnetosheath (Smith & Tsurutani, 1976; Tsurutani et al., 1982). Close to (or after) the saturation of whistlers, the electrons are less anisotropic, i.e., with $A_e \gtrsim 1$, and may still stimulate the proton mirror instability (Remya et al., 2013, 2017). A high growth rate predicted by the theory and associated with the mirror effects of electrons does not necessarily imply dynamical importance, since the saturated magnetic field is extremely low, and the influence on the particle temperatures is minimal (Noreen et al., 2017). Restricting to Maxwellian plasmas, these studies have ignored or treated only marginally the suprathermal populations, which are, however, ubiquitous in the solar wind and planetary magnetospheres.

It is therefore of particular interest to understand how the mirror instability can develop in the presence of suprathermal populations of electrons and protons, and when both species exhibit a temperature anisotropy $A_j = T_{j,\perp}/T_{j,\parallel} > 1$. To do so, we perform a comparative study using the new numerical solver, called DSHARK (Astfalk & Jenko, 2016; Astfalk et al., 2015), and developed for a full wave vector spectrum analysis of the instabilities in bi-Kappa distributed plasmas. The solver is adapted here for two alternative Kappa models to describe suprathermal populations with temperatures depending or not on the power index κ of the distribution; see equations (12) and (13). Suprathermal electrons and protons have been reported in terrestrial magnetosheath and in general in magnetosphere, and their distributions are well reproduced by the Kappa power laws (Formisano et al., 1973; Gosling et al., 1989; Masood & Schwartz, 2008; West & Buck, 1976; Williams et al., 1988). The plasma parameters adopted in our present study are inspired from the observations in terrestrial magnetosheath (Anderson & Fuselier, 1993; Samsonov et al., 2007; Soucek & Escoubet, 2011), but, given the extended range of values considered for the plasma beta parameters, temperature contrast, etc., the relevance of our results can extend to many other space plasma environments (e.g., planetary magnetosheaths and heliosheath). In order to gain a reliable understanding on the role played by the major species, namely, the electrons and protons, here we ignore any influence of heavier ions, which may have only a minor

and variable presence (1–6%) in the magnetosphere. Without a direct influence on mirror modes, heavier ions can instead inhibit the EMIC giving chances to mirror instability to develop (Price et al., 1986; Remya et al., 2013); see also in Maruca et al. (2012), who found negligible variations of the instability thresholds in the presence of 5% heavier ions.

The present study is focused on the solar wind conditions which may determine a cumulative (stimulating) effect of both species on mirror instabilities. We provide a detailed parametric analysis intended to describe the mutual effects of anisotropic electrons and protons and their suprathermal populations. Our paper is organized as follows. In section 2 we introduce in brief the general dispersion relation for an arbitrary propagation angle in a collisionless bi-Kappa distributed electron-proton plasma embedded in a uniform magnetic field. To motivate the present study, section 3 presents a short comparative analysis of the EMIC and mirror instabilities under the effects of anisotropic electrons ($A_e \gtrsim 1$) and their suprathermal components. The EMIC growth rates may be markedly inhibited by these effects, indicating a lower effectiveness of this instability (Shaaban et al., 2015, 2017). Mirror instability resulted from the interplay of anisotropic electrons and protons, and their suprathermal components are characterized in section 4. We show how the instability growth rates and thresholds change due to anisotropic electrons, the abundance of suprathermal populations, and the electrons-proton temperature contrast. The results of our present study are summarized and discussed in the last section.

2. Magnetized Bi-Kappa Plasmas: Wave Dispersion for Arbitrary Propagation

In this section we introduce the kinetic dispersion relation for the electromagnetic modes propagating in a collisionless and homogeneous electron-proton plasma at an arbitrary angle θ with respect to the background magnetic field $\mathbf{B}_0 = B_0 \hat{\mathbf{z}}$. Both species, i.e., the electrons (subscript $j = e$) and protons (subscript $j = p$), may exhibit temperature anisotropies $A_j = T_{j,\perp}/T_{j,\parallel} > 1$, and their velocity distributions are assumed well described by the bi-Kappa power laws

$$f_j = \frac{1}{\pi^{3/2} \theta_{j,\perp}^2 \theta_{j,\parallel}} \frac{\Gamma(\kappa_j + 1)}{\Gamma(\kappa_j - 1/2)} \left(1 + \frac{v_{\parallel}^2}{\kappa_j \theta_{j,\parallel}^2} + \frac{v_{\perp}^2}{\kappa_j \theta_{j,\perp}^2} \right)^{-\kappa_j - 1}, \quad (1)$$

where $\int d^3v f_j = 1$, $\kappa_j \geq 3/2$ is the power index, and $\theta_{j,\parallel,\perp}$ correspond to thermal velocities, respectively, parallel and perpendicular to the background magnetic field, and are defined by the kinetic temperature components, respectively,

$$T_{j,\parallel}^K = \frac{2\kappa_j}{2\kappa_j - 3} \frac{m_j}{2k_B} \theta_{j,\parallel}^2 \quad \text{and} \quad T_{j,\perp}^K = \frac{2\kappa_j}{2\kappa_j - 3} \frac{m_j}{2k_B} \theta_{j,\perp}^2. \quad (2)$$

The linear dispersion relation for the electromagnetic modes at an arbitrary angle with respect to the background magnetic field takes the following general form (Astfalk et al., 2015; Summers et al., 1994)

$$0 = \det D(\omega, k, \theta) \quad (3)$$

with

$$D(\omega, k, \theta) = \begin{vmatrix} 1 - \frac{c^2 k_{\parallel}^2}{\omega^2} + \epsilon_{xx} & \epsilon_{xy} & \frac{c^2 k_{\parallel} k_{\perp}}{\omega^2} + \epsilon_{xz} \\ \epsilon_{yx} & 1 - \frac{c^2 k_{\perp}^2}{\omega^2} + \epsilon_{yy} & \epsilon_{yz} \\ \frac{c^2 k_{\parallel} k_{\perp}}{\omega^2} + \epsilon_{zx} & \epsilon_{zy} & 1 - \frac{c^2 k_{\perp}^2}{\omega^2} + \epsilon_{zz} \end{vmatrix}, \quad (4)$$

and dielectric elements

$$\epsilon_{xx} = \sum_j \sum_{n=-\infty}^{n=+\infty} \frac{\omega_{pj}^2}{\omega^2} \frac{n^2}{\lambda_j^2} \left[\Lambda_j K_1 \int_0^\infty \frac{\mu J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda_j^2)^{\kappa_j+3/2}} + \left(\Lambda_j \xi_j + \frac{\omega}{k_{\parallel} \theta_{j,\parallel}} \right) K_2 \int_0^\infty \frac{\mu J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda_j^2)^{\kappa_j+2}} Z_{\kappa_j+1} \left(\xi_j \sqrt{\frac{\kappa_j+1}{1 + \mu^2/2\lambda_j^2}} \right) d\mu \right] \quad (5)$$

$$\epsilon_{xy} = -\epsilon_{yx} = \sum_j \sum_{n=-\infty}^{n=+\infty} \frac{\omega_{pj}^2}{\omega^2} \frac{in}{\lambda_j^2} \left[\Lambda_j K_1 \int_0^\infty \frac{\mu^2 J_n(\mu) J_n'(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+3/2}} + \left(\Lambda_j \xi_j + \frac{\omega}{k_{\parallel} \theta_{\parallel j}} \right) K_2 \int_0^\infty \frac{\mu^2 J_n(\mu) J_n'(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+2}} Z_{\kappa+1} \left(\xi_j \sqrt{\frac{\kappa+1}{1 + \mu^2/2\lambda}} \right) d\mu \right] \quad (6)$$

$$\epsilon_{yy} = \sum_j \sum_{n=-\infty}^{n=+\infty} \frac{\omega_{pj}^2}{\omega^2} \frac{1}{\lambda_j^2} \left[\Lambda_j K_1 \int_0^\infty \frac{\mu^3 J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+3/2}} + \left(\Lambda_j \xi_j + \frac{\omega}{k_{\parallel} \theta_{\parallel j}} \right) K_2 \int_0^\infty \frac{\mu^3 J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+2}} Z_{\kappa+1} \left(\xi_j \sqrt{\frac{\kappa+1}{1 + \mu^2/2\lambda}} \right) d\mu \right] \quad (7)$$

$$\epsilon_{xz} = \epsilon_{zx} = \sum_j \sum_{n=-\infty}^{n=+\infty} \frac{\omega_{pj}^2}{\omega^2} \frac{\theta_{\parallel j}}{\theta_{\perp j}} \frac{\sqrt{2}n}{\lambda_j^{3/2}} \left(\Lambda_j \xi_j + \frac{\omega}{k_{\parallel} \theta_{\parallel j}} \right) \left[K_1 \int_0^\infty \frac{\mu J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+3/2}} + \xi_j K_2 \int_0^\infty \frac{\mu J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+2}} Z_{\kappa+1} \left(\xi_j \sqrt{\frac{\kappa+1}{1 + \mu^2/2\lambda}} \right) d\mu \right] \quad (8)$$

$$\epsilon_{yz} = -\epsilon_{zy} = \sum_j \sum_{n=-\infty}^{n=+\infty} \frac{\omega_{pj}^2}{\omega^2} \frac{\theta_{\parallel j}}{\theta_{\perp j}} \frac{-\sqrt{2}i}{\lambda_j^{3/2}} \left(\Lambda_j \xi_j + \frac{\omega}{k_{\parallel} \theta_{\parallel j}} \right) \left[K_1 \int_0^\infty \frac{\mu^2 J_n(\mu) J_n'(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+3/2}} + \xi_j K_2 \int_0^\infty \frac{\mu^2 J_n(\mu) J_n'(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+2}} Z_{\kappa+1} \left(\xi_j \sqrt{\frac{\kappa+1}{1 + \mu^2/2\lambda}} \right) d\mu \right] \quad (9)$$

$$\epsilon_{zz} = \sum_j \sum_{n=-\infty}^{n=+\infty} \frac{\omega_{pj}^2}{\omega^2} \frac{\theta_{\parallel j}^2}{\theta_{\perp j}^2} \frac{2\xi_j}{\lambda_j^{3/2}} \left(\Lambda_j \xi_j + \frac{\omega}{k_{\parallel} \theta_{\parallel j}} \right) \left[K_1 \int_0^\infty \frac{\mu J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+3/2}} + \xi_j K_2 \int_0^\infty \frac{\mu J_n^2(\mu) d\mu}{(1 + \mu^2/2\lambda\kappa)^{\kappa+2}} Z_{\kappa+1} \left(\xi_j \sqrt{\frac{\kappa+1}{1 + \mu^2/2\lambda}} \right) d\mu \right] \quad (10)$$

where $J_n(\mu)$ are the Bessel functions of the first kind,

$$K_1 = \frac{\kappa^2 - 1/4}{\kappa^2}, \quad K_2 = \frac{\kappa - 1/2}{\kappa} \left(\frac{\kappa + 1}{\kappa} \right)^{1.5},$$

$$\xi_j = \frac{\omega - n\Omega_j}{k_{\parallel} \theta_{\parallel j}}, \quad \lambda_j = \frac{k_{\perp}^2 \theta_{\perp j}^2}{2\Omega_j^2}, \quad \Lambda_j = A_j - 1$$

and $Z_{\kappa}(\xi_j)$ is the plasma modified (Kappa) dispersion function (Summers et al., 1994).

$$Z_{\kappa}(\xi_j) = \frac{1}{\pi^{1/2} \kappa_j^{3/2}} \frac{\Gamma(\kappa_j)}{\Gamma(\kappa_j - 1/2)} \int_{-\infty}^{\infty} \frac{(1 + x^2/\kappa_j)^{-\kappa_j-1}}{x - \xi_j} dx, \quad \Im(\xi_j) > 0, \quad (11)$$

The influence of suprathermal populations is studied by varying the power index κ , where the standard bi-Maxwellian approach is recovered as a limit case for very large values of κ ($\kappa \rightarrow \infty$). Currently, two alternative approaches are invoked, assuming the kinetic temperature either dependent or independent of κ . A contrast between these two approaches have been shown already but only for parallel electromagnetic modes (Lazar et al., 2015, 2016; Shaaban et al., 2016), i.e., for $\theta = 0$. Lets give a brief description of these two approaches:

1. We call Kappa-1 the approach with κ -dependent temperatures, increasing in the presence of suprathermals, i.e., with decreasing κ

$$T_{\parallel,\perp}^K = \frac{2\kappa}{2\kappa - 3} T_{\parallel,\perp}^M > T_{\parallel,\perp}^M, \quad \beta_{\parallel,\perp}^K = \frac{2\kappa}{2\kappa - 3} \beta_{\parallel,\perp} > \beta_{\parallel,\perp}, \quad (12)$$

2. We call Kappa-2 the approach with κ -independent temperatures

$$T_{\parallel,\perp}^K = T_{\parallel,\perp}^M, \quad \beta_{\parallel,\perp}^K = \beta_{\parallel,\perp}, \quad (13)$$

Figure 1. Comparison between the effects of the electron temperature anisotropy $A_e = 1.5$ on both mirror instability (panel a) and EMIC (panel b) instability in the vicinity of maximum growth rate $\gamma_m/\Omega_p = 10^{-2}$. The plasma parameters are mentioned in each panel.

where $T_{\parallel,\perp}^M$ and $\beta_{\parallel,\perp}$ are, respectively, the temperatures and plasma betas defined for the Maxwellian limit $\kappa \rightarrow \infty$. We have to point out the relevance of a Kappa-1 approach which enables characterization of the suprathermal populations (that enhance the high-energy tails) and their effects by a direct comparison with the core of the distribution reproduced by the Maxwellian limit (Lazar et al., 2015, 2016). On the other hand, the relevance of a Kappa-2 approach is still unclear (Lazar et al., 2016).

3. Interlude: Mirror Versus EMIC

In order to motivate our interest for mirror instability, we start the analysis with a brief comparison with the EMIC instability for conditions involving anisotropic electrons and their suprathermal population.

Figure 1 shows the effect of anisotropic electrons with $A_e = 1.5$ on mirror (panel a) and EMIC (panel b) instabilities driven by the anisotropic protons with $A_p = 2.0$. Both species are assumed bi-Maxwellian and close to the energy equipartition conditions $\beta_{p,\parallel} = \beta_{e,\parallel} = 1$. Remya et al. (2013) have studied the effects of anisotropic electrons on mirror in combination with a minor component of heavier ions. The proton mirror solutions obtained for isotropic electrons (red solid lines in panel a) reproduce those obtained by Gary (1992) for the same plasma parameters. The growth rates of mirror instability are obtained for an oblique angle $\theta = 71^\circ$ and are enhanced by the electron anisotropy, while the EMIC instability (panel b) with maximum growth rates in parallel direction ($\theta = 0^\circ$) is inhibited by the same electron anisotropy. The effects of anisotropic electrons are clearly opposite, and even for a small anisotropy of electrons the mirror growth rates become 4 times greater than for isotropic electrons, and exceed the EMIC growth rates.

In Figure 2 the electrons are assumed bi-Kappa distributed with $\kappa_e = 4$, and modeled with a Kappa-1 approach. The other conditions as in Figure 1. The effect of anisotropic electrons on EMIC instability (panel b) does not change much in the presence of suprathermal electrons, but mirror growth rates (panel a) rates are highly enhanced, with more than 1 order of magnitude. Anisotropic electrons and their suprathermal

Figure 2. The same as in Figure 1 but for suprathermal electrons with $\kappa_e = 4$. The plasma parameters are mentioned in each panel.

Figure 3. Effects of the electron anisotropy $A_e > 1$ on the growth rates of mirror instabilities. The plasma parameters are mentioned in each panel.

population stimulate the mirror unstable modes and inhibit the EMIC instability. The effect on EMIC modes is indirect as the anisotropic electrons only change the wave dispersion properties and hence reduce the number of resonant protons (Shaaban et al., 2017).

4. Mirror Instability

In this section we present the results of a comprehensive study of the mirror instabilities triggered by the interplay of anisotropic electrons and protons. Our analysis starts with a standard representation assuming both the electron and proton species bi-Maxwellian distributed, and then we examine the effects of suprathermal populations as described by the bi-Kappa distribution function.

4.1. The Interplay of Anisotropic Electrons and Protons

If the velocity distributions are assumed bi-Maxwellian, mirror instability is stimulated when both the electron (subscript $j = e$) and proton (subscript $j = p$) populations are anisotropic with $A_j > 1$. Figure 3 displays unstable mirror solutions obtained at $\theta = 63^\circ$ from the interplay of the anisotropic electrons and protons with $A_p = 2.5$ and $\beta_{p||} = \beta_{e||} = 1$. Panel a shows the effect of electrons with relatively small anisotropies $A_e = 1.0, 1.3, 1.5$, and 1.7 , with mirror growth rates increasing with increasing the electron anisotropy and indicating a stimulation of the instability. For higher anisotropies, for example, for $A_e = 1.84 - 1.88$, in panel b, the range of unstable wave numbers increases considerably and the growth rates show two distinct peaks, a proton mirror peak at low wave numbers and second peak associated with a mirror effect driven by the electron anisotropy at higher wave numbers. The stability theory of anisotropic electrons with $T_\perp > T_\parallel$ predicts a whistler instability developing faster than the electron mirror (Gary & Karimabadi, 2006). In the presence of suprathermals this contrast maintains (a detailed study will be reported elsewhere) and may therefore explain why the electron mirror modes are not evident in the observations (Tsurutani, Echer, et al., 2011). The nonpropagating nature of the mirror modes is confirmed by the zero-frequency ($\omega_r = 0$) solutions for the full range of the unstable wave numbers (wave frequency ω_r is not shown here). Mirror growth rates with similar two-peaks

Figure 4. Growth rates of the proton mirror instability under the influence of suprathermal electrons in Kappa-1 approach in panel a and Kappa-2 approach in panel b. The propagation angle and plasma parameters are given in each panel.

Figure 5. The same as in Figure 4 but for a lower electron anisotropy $A_e = 1.5$, and larger electron parallel beta $\beta_{e||} = 2$. The other plasma parameters are given in each panel.

profiles have also been obtained in a recent quasi-linear study of the electron contribution to mirror instability (Noreen et al., 2017). For higher electron anisotropies the second peak becomes predominant and the other proton peak is only hardly distinguished.

4.2. Suprathermal Electrons

Ubiquitous in space plasmas, the suprathermal populations of electrons are well reproduced by the generalized Kappa power laws, with power index κ_e describing the high-energy tails of the observed velocity distributions. The electron power index can therefore be considered an additional key parameter that quantifies the free energy of the suprathermal populations. Here the electrons are assumed to be bi-Kappa distributed, while the much heavier protons are considered bi-Maxwellian.

We have already seen that the effects of anisotropic electrons highly depend on the level of their anisotropy. Growth rates displayed in Figure 4 are obtained at $\theta = 66^\circ$, for protons with $A_p = 2.25$ and $\beta_{p||} = \beta_{e||} = 1$, and electrons with a relatively small anisotropy $A_e = 1.5$. We study the effect of suprathermal electrons by varying $\kappa_e = 4, 6, 8, \infty$. Thus, for a Kappa-1 approach for the electrons (i.e., with temperature depending on κ_e) the proton mirror growth rates (panel a) increase with decreasing κ_e , while for a Kappa-2 approach the same growth rates do not show any influence (panel b). Instead, the EMIC growth rates are diminished with decreasing κ_e as shown in our previous section and to a more extent in Shaaban et al. (2016). If electrons are isotropic, i.e., $A_e = 1.0$, the effect of suprathermal electrons is negligible, for both Kappa-1 and Kappa-2 approaches.

Figure 5 presents the effects of suprathermal electrons for a higher (parallel) plasma beta, i.e., $\beta_{e||} = 2$, as given by a higher electron-proton temperature ratio $T_{e||}/T_{p||} = 2$, which here is chosen 2 times higher than in Figures 3. The growth rates may display a very clear two-peaks structure, for example, in panel b, and both peaks are enhanced with decreasing κ_e . For a Kappa-1 approach (panel a) the instability shows again a systematic stimulation in the presence of suprathermal electrons: the maximum growth rates and the range

Figure 6. Proton mirror growth rates under the effect of power index κ_p for a Kappa-1 approach in panel a and a Kappa-2 approach in panel b. The plasma parameters are mentioned in each panel.

Figure 7. Effects of electron anisotropy A_e (panel a) and their suprathermal population κ_e (panel b) on the proton mirror thresholds $\gamma_m/\Omega_p = 10^{-2}$ at $\theta = 66^\circ$. The plasma parameters are mentioned in each panel.

of unstable wave numbers increase with decreasing κ_e . Instead, for a Kappa-2 approach (panel b) only the peaks increase while the range of unstable wave numbers reduces with decreasing κ_e .

4.3. Suprathermal Protons

Here we consider bi-Kappa distributed protons and Maxwellian (isotropic) electrons, which allows us to extract only the effects of suprathermal protons. Figure 6 displays proton mirror growth rates derived at $\theta = 66^\circ$ for $\beta_{p,\parallel} = \beta_{e,\parallel} = 1$ and $A_p = 2.25$. The effects of suprathermal protons are outlined by varying $\kappa_p = 2, 6, \infty$. Again, a Kappa-1 approach, in panel a, appears to be more realistic, as it implies a systematic stimulation of the instability in the presence of suprathermal protons (lowering κ_p), while for a Kappa-2 approach the instability is inhibited.

Within a Kappa-1 approach the suprathermal particles show a systematic stimulation of mirror instability, while for a Kappa-2 approach the effect of suprathermal is not uniform, for example, Figures 4–6 (see also similar effects on the instabilities of firehose and cyclotron modes (Lazar et al., 2015; Shaaban et al., 2016)). These effects can be physically interpreted by the difference between Kappa approaches. Thus, Kappa 1 represents a partial energization of a Maxwellian population leading to a redistribution of a minor population from the core to the suprathermal tails, and a net increase of kinetic energy. In Kappa 2, the low energy core of the distribution may result from a cooling of an important fraction of the energetic particles from the Maxwellian tails, but overall the kinetic energy needs to be conserved reducing the dependence on kappa index in the stability calculation.

4.4. Proton Mirror Instability Thresholds

A more general perspective is provided by the contours derived for given values of maximum growth rates $\gamma_m/\Omega_p = 10^{-1}, 10^{-2}, 10^{-3}$, in terms of temperature anisotropy A_p and the parallel plasma beta $\beta_{p,\parallel}$. Lower levels close to the marginal condition of (in)stability ($\gamma_m \rightarrow 0$) are usually interpreted as thresholds of the instability, for example, $\gamma_m/\Omega_p = 10^{-2}, 10^{-3}$. In Figures 7 and 9 contours are computed for a (moderately) low level $\gamma_m/\Omega_p = 10^{-2}$, which enables us to compare with previous studies for bi-Maxwellian plasmas and without any influence from electrons (Hellinger et al., 2006; Kasper et al., 2003). Here the instability thresholds

Table 1

Fitting Parameters for Thresholds $\gamma_m/\Omega_p = 10^{-2}$

	Figure 7a			Figure 7b			Figure 9	
A_e	a	b	κ_e	a	b	κ_p	a	b
1.0	1.080	0.634	3	0.291	0.631	3	0.701	0.634
1.3	0.814	0.644	6	0.591	0.638	6	0.881	0.643
1.5	0.575	0.641	∞	0.705	0.645	∞	1.080	0.634
1.7	0.263	0.494

Figure 8. A comparison between the EMIC and mirror instability maximum growth rates γ_m/Ω_p as a function of the electron anisotropy A_e (panel a) and proton parallel beta $\beta_{p,||}$ (panel b) under the influence of the electron suprathermal populations and electron anisotropy. The plasma parameters are mentioned in each panel.

are derived only for a Kappa-1 approach (with κ -dependent temperatures), which appear to be more realistic; see the arguments above. These thresholds are fitted to an inverse correlation law (Gary & Wang, 1996; Shaaban et al., 2017)

$$A_p = 1 + \frac{a}{\beta_{p,||}}, \quad (14)$$

where the fitting parameters a and b are tabulated in Table 1.

Figure 7 displays the proton mirror thresholds ($\gamma_m/\Omega_p = 10^{-2}$) and show their variation under the effects of anisotropic electrons and their suprathermal populations. Top panel shows the proton anisotropy thresholds obtained for bi-Maxwellian electrons with $\beta_{e,||} = 1$ and different anisotropies $A_e = 1.0, 1.3, 1.5$, and 1.7 . The mirror thresholds decrease with increasing the electron anisotropy, confirming the stimulating effect of anisotropic electrons indicated by the growth rates in Figures 1 and 3. The instability threshold derived for isotropic electrons, i.e., solid black line in Figure 7, panel a, agrees with that provided by Hellinger et al. (2006). In panel b we present the effect of suprathermal electrons with a small anisotropy $A_e = 1.4$, and for different power indices $\kappa_e = 3, 6, \infty$. Thresholds decrease with enhancing the suprathermal electrons, confirming the results in Figure 4. Unifying these results, we can state that thresholds of proton mirror instability decrease significantly in the presence of anisotropic electrons, especially at low proton plasma betas, i.e., $\beta_{p,||} < 1$, and this effect is enhanced by the suprathermal electrons. Lower thresholds are associated with the instabilities highly stimulated by the anisotropic electrons, and, implicitly, with the enhanced fluctuations which may constrain the protons at lower anisotropies.

Figure 9. Effects of suprathermal protons ($\kappa_p = 3, 6, \infty$) on the proton mirror threshold $\gamma_m/\Omega_p = 10^{-2}$.

In order to emphasize the significant role played by the suprathermal populations in Figure 8 we identify new regimes of dominance of the mirror instability, which enables contrast with previous results. Remya et al. (2013) have ignored the effects of the suprathermal populations and found a stimulating effect of anisotropic electrons on mirror instability conditioned by the plasma beta, electron anisotropy, and the number density of heavier ions (n_a). For instance, for $\beta_p = 0.5$ and $n_a = 0.01n_p$ they found a dominance of mirror against EMIC for $A_e > 1.8$; see Figure 7 in Remya et al. (2013). Here in Figure 8 panel a, we show that suprathermal electrons ($\kappa_e = 3$) have a stronger effect, extending the dominance of mirror even in the absence of heavier ions, to a markedly lower threshold anisotropy $A_e > 1.29$. Moreover, the proton plasma beta ensuring the effectiveness of mirror can be significantly reduced if the anisotropy of protons is high enough: for example, if $A_p = 6$ our results in panel b show a dominance of mirror instability for $\beta_p > 0.015$ in the presence of suprathermal electrons with $A_e = 1.4$ and $\kappa_e = 3$. At lower plasma betas the instability is ignited by larger anisotropies of protons.

Figure 10. A comparison between the EMIC and mirror instability maximum growth rates γ_m/Ω_p as a function of the electron anisotropy A_e under the influence of the proton and electron suprathermal populations.

Figure 9 presents the effect of suprathermal protons, quantified by different values of $\kappa_p = 3, 6, \infty$, on the instability thresholds ($\gamma_m/\Omega_p = 10^{-2}$) derived for isotropic ($A_e = 1$), Maxwellian electrons with $\beta_{e,||} = 1$. The instability thresholds decrease with increasing the proton suprathermal populations, in agreement with the results in Figure 6, panel a and with those obtained by Leubner and Schupfer (2001) for similar conditions. We should note that these effects are less pronounced than the effects of suprathermal electrons found here above.

In Figure 10 we combine both the effects of suprathermal electrons and protons ($\kappa_e = 3$ and $\kappa_p = 3$), to identify the dominance regime of the mirror instability for the same parameters in Figure 8. The proton suprathermal populations stimulate the maximum growth rates of both the EMIC and mirror instabilities, with a slightly higher boost on the EMIC. Therefore, the dominance of the mirror instability requires a slightly higher electron anisotropy, i.e., $A_e > 1.31$, than that obtained in Figure 8 for Maxwellian protons ($\kappa_p \rightarrow \infty$).

4.5. The Influence of Temperature Contrast ($T_{e,||}/T_{p,||}$)

In Figure 11 we show the variations of the maximum growth rates (γ_m/Ω_p) of proton mirror instability (panel a) and the propagation angle (panel b) with the electron-proton temperature contrast $T_{e,||}/T_{p,||}$. To quantify the effects of suprathermal electrons, these variations are obtained for different values of $\kappa_e = 4, 6, \infty$. In panel a the maximum growth rates are derived at $\theta = 66^\circ$ for a proton anisotropy $A_p = 2$, $\kappa_p = 4$ and in the presence of anisotropic electrons with $A_e = 1.2$. Growth rates increase with increasing the temperature contrast $T_{e,||}/T_{p,||}$, and this effect is stimulated by the suprathermal electrons. In panel b the propagation angle is derived for $A_p = 2$, $\beta_p = 1$, $\kappa_p \rightarrow \infty$, $A_e = 1.2$, and $\gamma_m = 0.01\Omega_p$. This angle decreases with increasing $T_{e,||}/T_{p,||}$ and with enhancing the suprathermal electrons. The instability becomes more effective in the presence of suprathermals, reaching higher growth rates at oblique propagation angles, and for lower temperature contrasts between electrons and protons. Two additional remarks can be made here. First, these results are obtained for an extended range of values for the electron-proton temperature ratio, which include conditions typical for terrestrial magnetosheath, where this ratio is small (≤ 1) (Wang et al., 2012) or for the heliosheath, where the electrons (although not measured directly) appear to be hotter than protons (see Chalov & Fahr, 2013, and references therein). Second, we adopt a low anisotropy of electrons (i.e., $A_e = 1.2$), which is less susceptible to concurrent instabilities (e.g., whistlers), and can also persist after a quick relaxation from larger deviations from isotropy, with a remarkable influence on mirror instability (see Ahmadi et al., 2017; Remya et al., 2013, 2017). Our present results support the effectiveness of weakly anisotropic electrons and show that their stimulating role is boosted in the presence of suprathermal populations.

Figure 11. Effects of suprathermal electrons ($\kappa_e = 4, 6, \infty$), on the maximum growth rate of proton mirror instability γ_m/Ω_p (panel a), and the propagation angle θ for a given $\gamma_m = 0.01\Omega_p$ (panel b). Each quantity is derived as a function of electron-proton temperature contrast $T_{e,||}/T_{p,||}$. The plasma parameters are mentioned in each panel.

5. Discussions and Conclusions

In this paper we have presented a parametric analysis of the mirror instability resulted from the interplay of anisotropic electrons ($A_e > 1$) and protons ($A_p > 1$) and their suprathermal populations, focusing on conditions typically encountered in planetary magnetosheath and, in particular, in the heliosheath, where mirror modes are observed. Accordingly to these observations, in the kinetic approach the velocity distributions of plasma particles have been assumed well described by the generalized bi-Kappa distribution function that enables a direct comparison with the standard bi-Maxwellian in the limit of $\kappa \rightarrow \infty$. We have solved the general dispersion relation for an arbitrary propagation with respect to the magnetic field by using a numerical solver called DSHARK (Astfalk et al., 2015), which provides the exact mirror mode solutions.

Mirror instabilities driven by the bi-Kappa populations have been studied using two alternative approaches (Lazar et al., 2015, 2016), namely, Kappa-1 approach that assumes κ -dependent temperatures and provides a realistic characterization of suprathermal populations, and Kappa-2 formalism with κ -independent temperatures, which are less relevant but simpler and therefore preferred in computations. Within a Kappa-1 approach, suprathermal electrons have an important stimulating effect on the instability, enhancing the (maximum) growth rates and extending the range of unstable wave numbers with lowering κ_e (e.g., in Figures 4 and 5). The effects of suprathermal protons become significant when the instability is mainly controlled by the anisotropic protons: growth rates and the range of unstable wave numbers are enhanced with decreasing κ_p , but this stimulation is less prominent than that determined by the suprathermal electrons. Instead, a Kappa-2 approach leads to nonuniform variations of growth rates (as for other kinetic instabilities (Lazar et al., 2015; Shaaban et al., 2017)); the effects of suprathermal populations cannot be easily defined and we therefore avoid to discuss here.

The stimulating effects of the anisotropic electrons and suprathermal populations have been found characteristic to mirror instability over a large variety of physical conditions. Thus, Figures 7 and 9 show these effects on contours of constant maximum growth rates for a wide range of values of the plasma beta parameter, i.e., $0.01 \leq \beta_{p,\parallel} \leq 100$, while Figures 8 and 10 display by contrast the effects of suprathermals on both the mirror and EMIC instabilities. It becomes straightforward to compare with the results in Remya et al. (2013), who studied the effects of anisotropic electrons in the presence of a minor component of heavier ions but in the absence of suprathermal populations. Heavier ions are ignored here, with the main intention to isolate and describe the effects of major species and their suprathermal components. Even in the absence of heavier ions, suprathermals are found to play a major role, extending the dominance regime of mirror instability to markedly lower thresholds of temperature anisotropy and proton plasma beta. In addition, Figure 11 shows that mirror (maximum) growth rates are enhanced with increasing the electron-proton temperature contrast (panel a), especially when electrons are hotter than protons (see also Figure 5 and the analysis in section 4.5). This condition can be implicitly satisfied in the presence of suprathermal (hotter) populations, and the variations with κ_e and κ_p indicate a cumulative effect with a significant stimulation of the instability.

We conclude stating that the present study unveils new regimes of mirror instability when the velocity distributions of electrons and protons are well described by the generalized bi-Kappa distribution functions. The instability is stimulated by the interplay of anisotropic electrons and protons and their suprathermal populations, offering a plausible explanation for the mirror modes observed in planetary magnetosheaths and other space plasma environments (e.g., heliosheath) where these conditions are naturally satisfied. Present results should motivate a more extended quasi-linear/nonlinear analysis of this instability in the presence of suprathermal populations, to outline their effects by contrasting to bi-Maxwellian plasmas (Noreen et al., 2017) and estimate the saturated mirror fields and compare them with the fluctuations reported by the observations.

References

- Ahmadi, N., Germaschewski, K., & Raeder, J. (2016). Effects of electron temperature anisotropy on proton mirror instability evolution. *Journal of Geophysical Research: Space Physics*, 121, 5350–5365. <https://doi.org/10.1002/2016JA023148>
- Ahmadi, N., Germaschewski, K., & Raeder, J. (2017). Reply to comment by Remya et al. on "Effects of electron temperature anisotropy on proton mirror instability evolution". *Journal of Geophysical Research: Space Physics*, 122, 748–752. <https://doi.org/10.1002/2016JA023452>
- Anderson, B., & Fuselier, S. (1993). Magnetic pulsations from 0.1 to 4.0 Hz and associated plasma properties in the Earth's subsolar magnetosheath and plasma depletion layer. *Journal of Geophysical Research*, 98(A2), 1461–1479.
- Astfalk, P., & Jenko, F. (2016). Parallel and oblique firehose instability thresholds for bi-kappa distributed protons. *Journal of Geophysical Research: Space Physics*, 121, 2842–2852. <https://doi.org/10.1002/2015JA022267>

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- Astfalk, P., Görler, T., & Jenko, F. (2015). DSHARK: A dispersion relation solver for obliquely propagating waves in bi-kappa-distributed plasmas. *Journal of Geophysical Research: Space Physics*, 120, 7107–7120. <https://doi.org/10.1002/2015JA021507>
- Chalov, S., & Fahr, H. (2013). The role of solar wind electrons at the solar wind termination shock. *Monthly Notices of the Royal Astronomical Society: Letters*, 433(1), L40–L43.
- Chandrasekhar, S., Kaufman, A. N., & Watson, K. M. (1958). The stability of the pinch. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* (Vol. 245, pp. 435–455). The Royal Society.
- Erds, G., & Balogh, A. (1996). Statistical properties of mirror mode structures observed by Ulysses in the magnetosheath of Jupiter. *Journal of Geophysical Research*, 101(A1), 1–12.
- Formisano, V., Moreno, G., Palmiotto, F., & Hedgecock, P. C. (1973). Solar wind interaction with the Earth's magnetic field: 1. Magnetosheath. *Journal of Geophysical Research*, 78(19), 3714–3730. <https://doi.org/10.1029/JA078i019p03714>
- Gary, S. P. (1992). The mirror and ion cyclotron anisotropy instabilities. *Journal of Geophysical Research*, 97(A6), 8519–8529.
- Gary, S. P., & Karimabadi, H. (2006). Linear theory of electron temperature anisotropy instabilities: Whistler, mirror, and Weibel. *Journal of Geophysical Research*, 111, A11224. <https://doi.org/10.1029/2006JA011764>
- Gary, S. P., & Wang, J. (1996). Whistler instability: Electron anisotropy upper bound. *Journal of Geophysical Research*, 101(A5), 10,749–10,754.
- Glassmeier, K. H., Motschmann, U., Mazelle, C., Neubauer, F. M., Sauer, K., Fuselier, S. A., et al. (1993). Mirror modes and fast magnetoacoustic waves near the magnetic pileup boundary of comet P/Halley. *Journal of Geophysical Research*, 98(A12), 20,955–20,964. <https://doi.org/10.1029/93JA02582>
- Gosling, J. T., Thomsen, M. F., Bame, S. J., & Russell, C. T. (1989). Suprathermal electrons at Earth's bow shock. *Journal of Geophysical Research*, 94(A8), 10,011–10,025. <https://doi.org/10.1029/JA094iA08p10011>
- Hasegawa, A. (1969). Drift mirror instability in the magnetosphere. *The Physics of Fluids*, 12(12), 2642–2650.
- Hasegawa, A., & Tsurutani, B. T. (2011). Mirror mode expansion in planetary magnetosheaths: Bohm-like diffusion. *Physical Review Letters*, 107(24), 245005.
- Hellinger, P., Trávníček, P., Kasper, J. C., & Lazarus, A. J. (2006). Solar wind proton temperature anisotropy: Linear theory and WIND/SWE observations. *Geophysical Research Letters*, 33, L09101. <https://doi.org/10.1029/2006GL025925>
- Kasper, J. C., Lazarus, A. J., Gary, S. P., & Szabo, A. (2003). Solar wind temperature anisotropies. In *AIP Conference Proceedings* (pp. 538–541). IOP Institute Of Physics publishing LTD.
- Lazar, M., Schlickeiser, R., & Poedts, S. (2012). Suprathermal particle populations in the solar wind and corona. In M. Lazar (Ed.), *Exploring the Solar Wind* (241 pp.). Rijeka, Croatia: InTech. Retrieved from <http://www.intechopen.com/books/exploring-the-solar-wind/>
- Lazar, M., Poedts, S., & Fichtner, H. (2015). Destabilizing effects of the suprathermal populations in the solar wind. *Astronomy & Astrophysics*, 582, A124.
- Lazar, M., Fichtner, H., & Yoon, P. H. (2016). On the interpretation and applicability of κ -distributions. *Astronomy & Astrophysics*, 589, A39.
- Leubner, M. P., & Schupfer, N. (2000). Mirror instability thresholds in suprathermal space plasmas. *Journal of Geophysical Research*, 105(A12), 27,387–27,391.
- Leubner, M. P., & Schupfer, N. (2001). A general kinetic mirror instability criterion for space applications. *Journal of Geophysical Research*, 106(A7), 12,993–12,998.
- Liu, Y., Richardson, J., Belcher, J., Kasper, J., & Skoug, R. (2006). Plasma depletion and mirror waves ahead of interplanetary coronal mass ejections. *Journal of Geophysical Research*, 111, A09108. <https://doi.org/10.1029/2006JA011723>
- Maruca, B. A., Kasper, J. C., & Gary, S. P. (2012). Instability-driven limits on helium temperature anisotropy in the solar wind: Observations and linear vlasov analysis. *The Astrophysical Journal*, 748(2), 137.
- Masood, W., & Schwartz, S. (2008). Observations of the development of electron temperature anisotropies in Earth's magnetosheath. *Journal of Geophysical Research*, 113, A01216. <https://doi.org/10.1029/2007JA012715>
- McKean, M., Gary, S., & Winske, D. (1993). Kinetic physics of the mirror instability. *Journal of Geophysical Research*, 98(A12), 21,313–21,321.
- Narita, Y., Plaschke, F., Nakamura, R., Baumjohann, W., Magnes, W., Fischer, D., et al. (2016). Wave telescope technique for MMS magnetometer. *Geophysical Research Letters*, 43, 4774–4780. <https://doi.org/10.1002/2016GL069035>
- Noreen, N., Yoon, P. H., López, R. A., & Zaheer, S. (2017). Electron contribution in mirror instability in quasilinear regime. *Journal of Geophysical Research: Space Physics*, 22, 6978–6990. <https://doi.org/10.1002/2017JA024248>
- Pantellini, F. E., & Schwartz, S. J. (1995). Electron temperature instability effects in the linear proton mirror instability. *Journal of Geophysical Research*, 100, 3539–3549.
- Pierrard, V., & Lazar, M. (2010). Kappa distributions: Theory and applications in space plasmas. *Solar Physics*, 267(1), 153–174.
- Pokhotelov, O. A., Balikhin, M. A., Alleyne, H. S.-C. K., & Onishchenko, O. G. (2000). Mirror instability with finite electron temperature effects. *Journal of Geophysical Research*, 105(A2), 2393–2401.
- Pokhotelov, O. A., Treumann, R. A., Sagdeev, R. Z., Balikhin, M. A., Onishchenko, O. G., Pavlenko, V. P., et al. (2002). Linear theory of the mirror instability in non-Maxwellian space plasmas. *Journal of Geophysical Research*, 107(A10), 1312. <https://doi.org/10.1029/2001JA009125>
- Price, C. P., Swift, D. W., & Lee, L.-C. (1986). Numerical simulation of nonoscillatory mirror waves at the Earth's magnetosheath. *Journal of Geophysical Research*, 91(A1), 101–112.
- Remya, B., Reddy, R., Tsurutani, B., Lakhina, G., & Echer, E. (2013). Ion temperature anisotropy instabilities in planetary magnetosheaths. *Journal of Geophysical Research: Space Physics*, 118, 785–793. <https://doi.org/10.1002/jgra.50091>
- Remya, B., Reddy, R. V., Tsurutani, B. T., & Lakhina, G. S. (2017). Comment on “Effects of electron temperature anisotropy on proton mirror instability evolution” by Ahmadi et al. (2016). *Journal of Geophysical Research: Space Physics*, 122, 745–747. <https://doi.org/10.1002/2016JA023148>
- Riquelme, M. A., Quataert, E., & Verscharen, D. (2015). Particle-in-cell simulations of continuously driven mirror and ion cyclotron instabilities in high beta astrophysical and heliospheric plasmas. *The Astrophysical Journal*, 800(1), 27.
- Russell, C. T., Blanco-Cano, X., Jian, L. K., & Luhmann, J. G. (2009). Mirror-mode storms: Stereo observations of protracted generation of small amplitude waves. *Geophysical Research Letters*, 36, L05106. <https://doi.org/10.1029/2008GL037113>
- Russell, C. T., Riedler, W., Schwingenschuh, K., & Yeroshenko, Y. (1987). Mirror instability in the magnetosphere of comet Halley. *Geophysical Research Letters*, 14(6), 644–647.
- Samsonov, A., Alexandrova, O., Lacombe, C., Maksimovic, M., & Gary, S. (2007). Proton temperature anisotropy in the magnetosheath: Comparison of 3-d MHD modelling with Cluster data. *Annales Geophysicae*, 25, 1157–1173.
- Shaaban, S. M., Lazar, M., Poedts, S., & Elhanbaly, A. (2015). Effects of electrons on the electromagnetic ion cyclotron instability: Solar wind implications. *The Astrophysical Journal*, 814(1), 34.
- Shaaban, S. M., Lazar, M., Poedts, S., & Elhanbaly, A. (2016). Effects of suprathermal electrons on the proton temperature anisotropy in space plasmas: Electromagnetic ion-cyclotron instability. *Astrophysics and Space Science*, 361(6), 1–12.

- Shaaban, S. M., Lazar, M., Poedts, S., & Elhanbaly, A. (2017). Shaping the solar wind temperature anisotropy by the interplay of electron and proton instabilities. *Astrophysics and Space Science*, 362(1), 13. <https://doi.org/10.1007/s10509-016-2994-7>
- Shoji, M., Omura, Y., Tsurutani, B. T., Verkhoglyadova, O. P., & Lembege, B. (2009). Mirror instability and I-mode electromagnetic ion cyclotron instability: Competition in the Earth's magnetosheath. *Journal of Geophysical Research*, 114, A10203. <https://doi.org/10.1029/2008JA014038>
- Smith, E. J., & Tsurutani, B. T. (1976). Magnetosheath lion roars. *Journal of Geophysical Research*, 81(13), 2261–2266.
- Soucek, J., & Escoubet, C. (2011). Cluster observations of trapped ions interacting with magnetosheath mirror modes. In *Annales Geophysicae* (Vol. 29, 1049 pp.). Copernicus GmbH.
- Southwood, D. J., & Kivelson, G. (1993). Mirror instability: 1. Physical mechanism of linear instability. *Journal of Geophysical Research*, 98, 9181–9187.
- Summers, D., Xue, S., & Thorne, R. M. (1994). Calculation of the dielectric tensor for a generalized Lorentzian (κ) distribution function. *Physics of Plasmas*, 1(6), 2012–2025.
- Tajiri, M. (1967). Propagation of hydromagnetic waves in collisionless plasma. II. Kinetic approach. *Journal of the Physical Society of Japan*, 22(6), 1482–1494.
- Tsurutani, B., Smith, E., Anderson, R., Ogilvie, K., Scudder, J., Baker, D., et al. (1982). Lion roars and nonoscillatory drift mirror waves in the magnetosheath. *Journal of Geophysical Research*, 87(A8), 6060–6072.
- Tsurutani, B. T., Echer, E., Verkhoglyadova, O. P., Lakhina, G. S., & Guarnieri, F. (2011). Mirror instability upstream of the termination shock (TS) and in the heliosheath. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73(11), 1398–1404.
- Tsurutani, B. T., Lakhina, G. S., Smith, E. J., Buti, B., Moses, S. L., Coroniti, F. V., et al. (1999). Mirror mode structures and ELF plasma waves in the Giacobini-Zinner magnetosheath. *Nonlinear Processes in Geophysics*, 6(3/4), 229–234. <https://doi.org/10.5194/npg-6-229-1999>
- Tsurutani, B. T., Lakhina, G. S., Verkhoglyadova, O. P., Echer, E., Guarnieri, F. L., Narita, Y., et al. (2011). Magnetosheath and heliosheath mirror mode structures, interplanetary magnetic decreases, and linear magnetic decreases: Differences and distinguishing features. *Journal of Geophysical Research*, 116, A02103. <https://doi.org/10.1029/2010JA015913>
- Tsurutani, B. T., Southwood, D. J., Smith, E. J., & Balogh, A. (1992). Nonlinear magnetosonic waves and mirror mode structures in the March 1991 Ulysses interplanetary event. *Geophysical Research Letters*, 19(12), 1267–1270.
- Volwerk, M., Schmid, D., Tsurutani, B. T., Delva, M., Plaschke, F., Narita, Y., et al. (2016). Mirror mode waves in Venus's magnetosheath: Solar minimum vs. solar maximum. *Annales Geophysicae*, 34(11), 1099–1108. copyright - Copyright Copernicus GmbH 2016; Last updated - 2016-11-23.
- Volwerk, M., Zhang, T., Delva, M., Vörös, Z., Baumjohann, W., & Glassmeier, K.-H. (2008). First identification of mirror mode waves in Venus' magnetosheath? *Geophysical Research Letters*, 35, L12204. <https://doi.org/10.1029/2008GL033621>
- Vörös, Z. (2011). Magnetic reconnection associated fluctuations in the deep magnetotail: Artemis results. *Nonlinear Processes in Geophysics*, 18(6), 861–869.
- Wang, C.-P., Gkioulidou, M., Lyons, L. R., & Angelopoulos, V. (2012). Spatial distributions of the ion to electron temperature ratio in the magnetosheath and plasma sheet. *Journal of Geophysical Research*, 117, A08215. <https://doi.org/10.1029/2012JA017658>
- West, H. I., & Buck, R. M. (1976). Observations of > 100-keV protons in the Earth's magnetosheath. *Journal of Geophysical Research*, 81(4), 569–584.
- Williams, D., Mitchell, D., Frank, L., & Eastman, T. (1988). Three-dimensional magnetosheath plasma ion distributions from 200 eV to 2 MeV. *Journal of Geophysical Research: Space Physics*, 93(A11), 12,783–12,794.
- Yoon, P. H., & Seough, J. (2012). Quasilinear theory of anisotropy-beta relation for combined mirror and proton cyclotron instabilities. *Journal of Geophysical Research*, 117, A08102. <https://doi.org/10.1029/2012JA017697>