Stasiewicz Reply: In their Comment [1], Pokhotelov, Balikhin, Sagdeev, and Treumann (PBST) state that the model of nonlinear waves in anisotropic plasmas described in [2], applied to mirror structures in [3], and extended by including electron inertia effects in [4], is ''intrinsically self-contradictory and incorrect'' because it does not contain subtle effects of resonant particles. To support this claim, PBST refer to recent articles by Pokhotelov *et al.* [5,6] which address linear (small amplitude) aspects of kinetic mirror instability.

Mirror structures, which are the subject of this controversy, represent large amplitude periodic magnetic pulsations (3–60 s period in the satellite frame) measured in the magnetospheres of solar system planets and in the solar wind. In numerous experimental reports it has been established that these waves occur most commonly in regions of significant proton temperature anisotropy, $T_\perp > T_\parallel$, in a high-beta plasma ($\beta > 1$), exhibit anticorrelations between magnetic field δB and density δN perturbations, have small velocity with respect to the plasma, and propagate nearly perpendicular to $\mathbf{B}$. These strongly nonlinear structures with a typical size of 1000 km have been known for over 35 years [7], but there was no mathematical model capable to explain their properties.

Recently, the experimentally measured properties of mirror structures (in plasmas $0.1 < \beta < 10$) have been described and quantitatively modeled by using a self-consistent fluid model for a hot anisotropic plasma [2–4], based on empirically derived ion-pressure equations [8]. Contrary to PBST assertions, finite ion Larmor radius (FLR) effects have been included in these models through off-diagonal pressure tensor components, and thermal effects of $\beta_\perp$, $\beta_\parallel$. These results imply that: (a) mirror structures represent robust fluid effects (with pressure anisotropy) and the governing equations do not break down in the parameter range at $\beta \sim 10$ and (b) kinetic effects mentioned by PBST (viz. ''resonant particles'') play a much less important role for mirror structures than these authors have anticipated.

The small amplitude (linear) model of mirror instability constructed by PBST and other authors [5,6] is not applicable to observed structures which exhibit strong nonlinearities. Furthermore, the PBST model does not include the ion inertial length scale ($\lambda_i = c/\omega_{pi}$), which is the dispersive parameter that determines the growth rate and size of mirror structures, as well as properties of all other waves in Alfvén, magnetosonic, and sound branches [4]. This dispersive parameter cannot be disregarded or substituted by the thermal ion Larmor radius ($r_i = v_{ti}/\omega_{ci}$) in any linear or nonlinear analysis of mirror structures, even in cases when r_i is larger than λ_i.

PBST seem to be unaware that mirror structures can be described by properly applied fluid equations with ion-pressure anisotropy and ion inertia effects, and to incorrectly believe that the only proper tool to describe these structures is kinetic theory. However, the fluid model correctly reproduces: (i) amplitude ($\delta B/B \sim 100\%$), (ii) size of $\sim$1000 km, (iii) polarization, (iv) quasiperpendicular propagation, (v) sensitivity to temperature anisotropy, (vi) cnoidal wave appearance, (vii) electric currents within the structures, and (viii) small $\delta N/N$ variation, to name a few confirmed predictions. On the other hand, there exists no kinetic nonlinear theory of mirror structures that can be tested against observations.

The Comment [1] contains statements that appear to be unsupported (viz. related to unknown effects of magnetic viscosity for mirror structures) or not relevant (viz. related to parallel propagating modes). It also seems to disregard a general notion that physical theories are assessed mainly by comparisons with measurements. This has been done in the commented paper [2].

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Comment on "Theory and Observations of Slow-Mode Solitons in Space Plasmas"

Recently Stasiewicz [1] attempted to develop a nonlinear Hall-MHD theory of magnetic mirror modes in collisionless plasma stating that the finite ion inertial length $\lambda_i = v_A/\omega_{ci} \equiv c/\omega_{pi}$ (FIL) would be the relevant dispersion parameter (ω_{ci}, ω_{pi} ion-cyclotron and plasma frequency, respectively; v_A Alfvén speed) determining the evolution of ion modes including magnetic mirror modes. However, Hall-MHD when applied to mirror modes in high-β plasma is intrinsically self-contradictory and incorrect even in the linear approximation. Recall that mirror modes grow because of the subtle coupling [2] between resonant particles with velocities $v_\parallel \approx 0$ along the magnetic field $\mathbf{B}_0$ and the rest of plasma population. A decade ago it was shown [2] that their contribution to mirror mode dispersion dominates the contributions of any of the remaining fluid terms. In the analysis [1] of high-β mirror modes this crucial resonant contribution is ignored, a fundamental omission excluding the mirror mode from the very beginning. In low-β plasma the dispersion of MHD modes induced by FIL is important as is obvious from the (linearized) Hall-MHD dispersion relation $[1 - k_\parallel^2 v_A^2/\omega^2][1 + k^2\lambda_i^2 - k^2 v_A^2/\omega^2] = k^2\lambda_i^2$ coupling Alfvén and fast magnetosonic modes through FIL (ω frequency, k wave number $\mathbf{k}$ magnitude). For parallel propagation $k \rightarrow k_\parallel$, it reduces to cold plasma ion-cyclotron wave dispersion, $\omega^2 = k_\parallel^2 v_A^2(1 \mp \omega/\omega_{ci})$, for circularly polarized left (Alfvén) and right (magnetosonic) modes ($\mp$ signs). High-β conditions are much more complex because finite Larmor radius (FLR) effects come into play. In fact, FIL becomes increasingly negligible with increasing β since the two effects scale as $\mathrm{FIL}/\mathrm{FLR} \propto \beta^{-1}$. For example, the linear dispersion relation for parallel propagation reduces to $\omega^2 = k_\parallel^2 v_A^2[1 \mp \omega/\omega_{ci}(1 + \beta_\perp/2)]$. The term containing the (perpendicular) $\beta_\perp$ cannot be recovered from Hall-MHD in the analysis of [1]. For quasiperpendicular propagation in high-β plasma FLR dominates FIL, and $\lambda_i \lesssim \rho_i$, and Hall-MHD does not reproduce the correct mirror dispersion relation obtained from fully kinetic treatment unless supplemented with the missing "magnetic viscosity" $\hat{\pi}$ [3,4]. These are nonzero even for purely parallel wave propagation [cf. [5]]. Since linear theory *must* reproduce linear dispersion, this is an uncompromising argument against the correctness of [1] who cites [5] for justification. That Letter also misses the high-β correction terms thereby arriving at nonphysical conclusions. Magnetic viscosity is also not contained anywhere in the pressure tensor terms of [1]. For a proof one may consult the monographs [3]. In small FLR $k\rho_i \ll 1$, Alfvén waves decouple from the magnetosonic modes [6]. The fully kinetic treatment of the linear mirror instability [6] confirms this decoupling up to arbitrarily large ion-Larmor radii. Hence, for finite β, Alfvén perturbations have no effect on the mirror mode unless inhomogeneity is taken into account. The numerical calculations of [1] use values $\beta \sim 10$ when FLR $\gg$ FIL and Hall-MHD breaks down. As we note above, FLR could, in principle, be incorporated in [1] by adding the term $\nabla \cdot \hat{\pi}$ which, however, would change the results completely. Without this term the oversimplified Hall-MHD misses the crucial physical ingredient necessary in any correct nonlinear analysis of magnetic mirror modes. Its lack renders the conclusions of [1] on the mirror mode to be taken with caution.

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