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Reply to comment by H. Hasegawa on "Evolution of Kelvin-Helmholtz activity on the dusk flank magnetopause"

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[1] We demonstrate, on experimental grounds, that the justifications for the comment by *Hasegawa* [2009], hereinafter H09, on work done by *Foullon et al.* [2008], hereinafter F08, are not well founded.

[2] The comment by H09 questions the accuracy of the Kelvin-Helmholtz (KH) phase speeds, and consequently the wavelengths, derived using equation (4) of F08. This equation is applied to a pair of bounding surfaces or fronts, which represent (a) the inward and (b) the following outward motions of the boundary layer adjacent to the magnetopause, as detected by the Cluster spacecraft (there are no traversals of the magnetopause, contrary to statements by H09). H09 advocates the inclusion of a correction term and the omission of results for one of the two fronts (b). With this correction and the restriction to one front (a), H09 claims agreement with "rough" scale size estimates of vortices in the boundary layer given by *Hasegawa et al.* [2004]. Since F08 and H09 give detailed descriptions of their respective methods, we will not repeat them here. However, we point out some reservations we have on the derivation and argument provided by H09.

[3] Figure 1a of H09 describes the simple geometry of a surface wave, steepened at its leading edge (as opposed to the geometry of a KH vortex). Associated with Figure 1a is an equation (H09, equation (2)) which equates the velocity vector, normal to a given bounding surface, with a vector projection of the KH "phase speed" in the direction of the surface normal. A condition for this equation (2) to be valid is that the presumed phase speeds for the two points should be the same. Yet, H09 obtains "phase speeds," $V_{ph,a}$ and $V_{ph,b}$, which differ between the two points by a factor of 2 or more. H09 applies equation (2) using directions and speeds of the front motions derived by F08 from four-spacecraft timing analysis. The directions are given with respect to an undisturbed plane determined by F08 from a solar-wind-driven magnetopause model. Instead of taking a critical look at his own method for deriving the phase speed of the KH wave, H09 attributes the difference to supposedly nonreliable results for the outward motion (b), derived by F08. The claim is that this nonreliability is caused by nonlinear effects supposedly more pronounced on this bounding surface, which corresponds to the leading (steeper) front. This latter argument is used to justify why H09 disregards $V_{ph,b}$ and thus selects only the largest "phase speed" of the two points, $V_{ph,a}$, on the trailing edge, to calculate the wavelength. This comes as no surprise since, for one particular time interval, this larger value provides closer agreement with the ion velocity measurements, which *Hasegawa et al.* [2004] used to estimate the wavelength. We demonstrate below that the justifications for this line of reasoning are not well founded.

[4] F08 studied five oscillatory structures in separate time intervals, denoted A to E. There are several previous studies of magnetopause KH waves using the multispacecraft capabilities of Cluster [*Gustafsson et al.*, 2001; *Owen et al.*, 2004; *Hasegawa et al.*, 2004; *Nykyri et al.*, 2006; *Lund et al.*, 2006] to date with spacecraft separations an order of 10 times smaller than the inferred size of the KH structures. The relatively small spacecraft separation is suited to sample a quasi-planar subsection of the waveform. F08 apply the four-spacecraft timing method to two distinct data sets: (1) magnetic field (sunward) component, B_m, in a boundary layer coordinate system (**l**, **m**, **n**) (near the equatorial plane and on the duskside of the magnetotail), and (2) electron perpendicular temperature, $T_{e,\perp}$ (as pioneered by *Owen et al.* [2004]). The average results, $V_{k,a}$, $V_{k,b}$, and also the aggregate results, $V_{k,lm}$ (cf. F08, equation (4)), presented in F08's Table 5, contain error estimates. These error estimates are not reproduced in H09's Table 1, despite the fact that they would show, for the structures A and B, a range of values of $V_{ph,b}$ (from the propagation of errors that one would obtain on the leading edge with H09 equation (2)) that overlaps or falls within the F08 error estimates of $V_{k,lm}$. Further comparisons could include corrections for the orientation differences of the $\hat{\mathbf{k}}_\mathbf{a}$ and $\hat{\mathbf{k}}_\mathbf{b}$ vectors on the *lm* plane, which are apparently neglected in the H09 equation (2).

[5] The arguments used by H09 to question the reliability of the methodology used by F08 to determine motion speeds, $V_{k,b}$, and normals, $\hat{\mathbf{k}}_\mathbf{b}$, on the leading fronts do not withstand scrutiny. First of all, in referring to potential problems using a perturbed magnetic field data set shown in Figure 8 of F08, H09 fails to take account of the facts that

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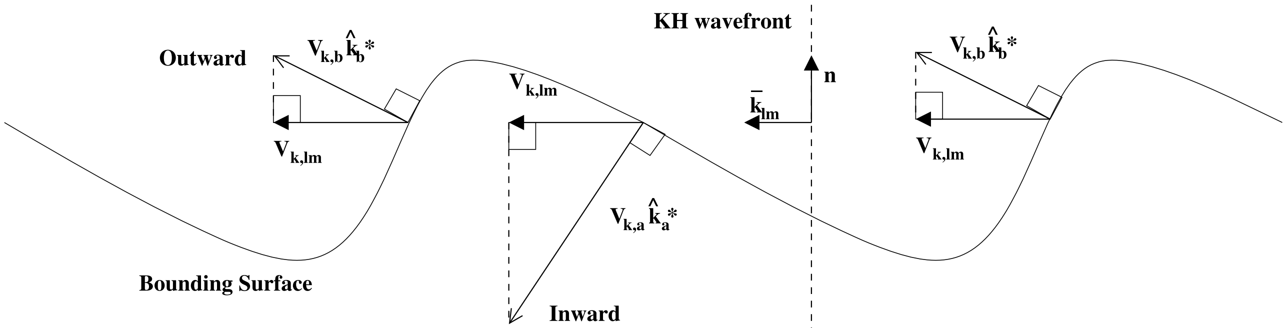

Figure 1. Schematic waveform of a KH wave propagating in the $\bar{k}_{lm}$ direction (to the left), showing the relationship between the phase speed, $V_{k,lm}$, and the velocities $V_{k,a}$ and $V_{k,b}$ measured in the directions $\hat{\mathbf{k}}_\mathbf{a}$ and $\hat{\mathbf{k}}_\mathbf{b}$, respectively, normal to a pair of bounding surfaces. The star symbol indicates that the values are projected in the ($\bar{k}_{lm}$, n) plane. $V_{k,a}$ and $V_{k,b}$ are apparent speeds along the surface normals.

(1) F08 developed a multiscale approach (paragraph 45) in order to determine the times of the main front passage; (2) the four-spacecraft timing analysis used by F08 was not just performed on the boundaries of oscillatory structures in the time series of B_m, but also on the time series of $T_{e,\perp}$ (see F08's Figure 8 and paragraphs 44 and 45). In the $T_{e,\perp}$ data set, temporal variations corresponding to those in the magnetic field data set are absent. The four-spacecraft timing results obtained are consistent between data sets. This approach is further justified with the use of error estimates on the combined results. Last, on the front (b), the second discontinuity in Figure 8 of F08, there is a noticeable (near half a minute) delay between timings used in each data set. This delay and the good agreement between the results derived from the two data sets indicate that the speed and direction of the leading front do not vary much along its steep profile (see Figure 1). Given this weight of consistent evidence, we believe this *is* therefore a *reliable* result.

[6] In contrast, we note that on the trailing front (a), chosen by H09 to derive the "phase speed," the agreement between the two data sets is not as good (compare error estimates of $V_{k,a}$ and $V_{k,b}$ in Table 4 of F08). This is particularly true for interval A, where the steepness angle $\phi_{k,a} = 86^\circ$ is the largest (i.e., a trailing front with a very flat profile). Taking the error estimates into account would yield a large range of estimates for the "phase speeds" $V_{ph,a}$ (the lower estimates of $V_{ph,a}$ are still much larger than the corresponding upper estimates of $V_{ph,b}$), which is completely ignored by H09. We believe therefore that the H09 values of $V_{ph,a}$ are not accurate.

[7] A second argument invoked by H09 against the reliability of the normal determination for the leading edge is a variable z_{GSM} component of the $\hat{\mathbf{k}}_\mathbf{b}$ vector between time intervals. H09 refers to Table 4 of F08, where the GSM components are averages but were unfortunately not normalized. For proper comparison, the components must be normalized. However, F08 choose instead to refer to elevation angles $\theta_{k,a}$ and $\theta_{k,b}$ for the trailing and leading fronts (F08's equation (6) and Table 5), in order to characterize the north-south deviations from the *mn* plane. They are not only more accurate for interpreting the north-south deviations in the boundary normal coordinate system, but they also show a consistent (mostly southward) component of propagation between the pair of bounding fronts for each interval (in interval E, the propagation directions are also consistent but northward). This indicates that the normal determinations obtained by F08 are likely to be correct at both fronts and can be combined between the two fronts in the average angle θ_k, for separate intervals. The variability of this parameter (given within error bars) between time intervals is illustrated in Figure 10c (middle) and Figure 10d (right) of F08 and is part of the results found and discussed in paragraphs 64 and 65 of F08. The latter plot, in particular, shows that the θ_k angles are ordered with the boundary layer thickness, confirming the relevance of the variability for interpreting the data.

[8] Finally, H09 suggests the use of single-spacecraft methods to check the validity of the results by F08. We note that (1) the four-spacecraft timing method used by F08 is more robust and leads in general to more reliable results than the single-spacecraft techniques for planar geometries and (2) we have already obtained consistent estimates between two different data sets, including a temperature data set displaying sharp transitions between adjacent plasma environments. As in the work of *Owen et al.* [2004], the four-spacecraft timing method has been used by F08 to confirm the tailward steepening of the KH leading fronts. This is consistent with the growing phase of KH waves [*de Keyser et al.*, 2005], while we note that anomalous cases of magnetopause surface waves with opposite (sunward) steepened edges previously reported from two spacecraft observations by ISEE 1 and ISEE 2 [*Chen et al.*, 1993; *Chen and Kivelson*, 1993] appear to form in association with strong magnetosheath plasma acceleration [*Lavraud et al.*, 2007]. Of particular interest, among the results from the parameter space survey of F08, is the inverse dependence between the boundary layer thickness and the tailward steepening of the leading edge. Overall, given the physical significance of the geometries obtained, we believe that the undisturbed plane (the *lm* plane) and the bounding front normals have been correctly determined by F08. The findings of vortical [*Fairfield et al.*, 2000; *Hasegawa et al.*, 2004; *Fairfield et al.*, 2007] and multiwavelength (F08) structures do not preclude a large-scale coherent KH structure propagating in a particular direction and with a phase speed that connects its leading and trailing front. This is the phase speed that is required for calculating a meaningful wavelength.

[9] Overall, we do not see the need for any qualitative changes to the conclusions reached by F08. The most important results concerned the temporal changes in wavelength, between intervals, and not their absolute estimates (the correction factor proposed by H09 is irrelevant here as it does not vary significantly between intervals). The evidence found by F08 of an inverse dependence between the clock angle of the interplanetary magnetic field and the wavelength at the flank (F08's Figure 10a (left)), as expected when generated by the KH mechanism, confirms the significance of source regions and nonlinear development for interpreting observations of remotely generated KH waves (see F08 (section 5.3) and the model of *Farrugia et al.* [1998]).

[10] Nevertheless, for an absolute determination of the wavelength (useful to compare with simulation results as shown by F08 (paragraph 52)), we believe that the correction term proposed by H09 is *not justified* experimentally and therefore *not necessary* (in the time intervals studied and for any similar events). First, as noted above, the H09 corrections lead to different "phase speeds" (a) and (b), which invalidates the H09 equation (2), predicated as it is on their equality. In contrast, as illustrated in Figure 1, the vector projections by F08 of the motion velocities (a) and (b) in the chosen direction of propagation along the unperturbed boundary equate to comparable point phase speeds (a) and (b) (before average), as can be found in the relatively small error estimates of $V_{k,lm}$ given by F08 (Table 5). This shows that the KH wave retains its sawtooth shape as it propagates (within a relatively short time interval). As noted by F08 (paragraph 54) and contrary to H09's Figure 1, the motion speeds V_k are generally faster for inward motions (a) with flatter profiles, which confirm them as "full deprojections" of the phase speeds, in other words, apparent speeds along the surface normals, in agreement with our Figure 1. Last, owing to the difference in directions of inward and outward motions in the *lm* plane and assuming the simplest form of the KH wavefront to be a plane wave, F08 have taken the average of the normalized $\hat{\mathbf{k}}_\mathbf{a}$ and $\hat{\mathbf{k}}_\mathbf{b}$ vectors in the *lm* plane as the direction of propagation along the unperturbed boundary (the $\overline{\mathbf{k}}_\mathbf{lm}$ vector from F08 (equation (4))). In this plane wave approximation, it is reasonable to adopt a "straight" projection as done by F08; that is, the orthogonal component of vector projection is along **n** (vertical in Figure 1), in the plane of the KH wavefront, which is assumed to be perpendicular to the unperturbed magnetopause boundary. This reasonable working assumption is not the one guiding the projection method proposed by H09, based on a misleading figure, which is not representing the observations detailed by F08.

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