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Four-Spacecraft Magnetic Curvature Analysis on Kelvin-Helmholtz Waves in MHD Simulations

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Abstract. Four-spacecraft missions are probing the Earth's magnetospheric environment with high potential for revealing spatial and temporal scales of a variety of in-situ phenomena. Magnetic curvature is intrinsic to curved magnetic fields where the magnetic energy is stored in the form of magnetic tension. In-situ magnetic curvature has been resolved by the four-spacecraft technique called "magnetic curvature analysis" (MCA). We test the MCA on 2.5D MHD simulations of curved magnetic structures induced by Kelvin-Helmholtz (KH) waves, with increasing (regular) tetrahedron sizes of virtual spacecraft. We have found variations of the curvature vectors both in radii and orientations depending on the sizes of the tetrahedron. This is helpful to better understand the MCA measures when the technique is applied to in-situ data without knowing the scale sizes of plasma structures under consideration. This study lends support for cross-scale observations to better understand the nature of curvature and its role in plasma phenomena.

1. Introduction

The Earth's magnetosphere outer boundary, the magnetopause, is the site of fundamental plasma processes that allow the entry of solar wind plasma to the magnetosphere. Entry of plasma under southward IMF conditions is dominated by magnetic reconnection. Kelvin-Helmholtz (KH) instabilities, arising from a shear flow at the magnetopause boundary, have been proposed as a candidate mechanism for the penetration of solar wind plasma, via magnetic reconnection and turbulence inside rolled-up KH vortices. Entry via KH instabilities is believed to occur under northward IMF conditions when magnetic reconnection at the dayside magnetopause is less dominant. Numerous observations of KH waves at the magnetopause have been studied by the four-spacecraft *Cluster* (e.g., Foullon *et al.* 2008) and recently the Magnetospheric Multiscale (MMS) missions (e.g., Eriksson *et al.* 2016). Unlike single spacecraft, four spacecraft which form tetrahedron configurations can resolve 3D plasma geometries at their barycentre. A plasma characteristic such as 'magnetic curvature' can influence properties of plasma waves and instabilities, and motion types of charged particles. In-situ magnetic curvature has been resolved in current sheets by the four-spacecraft technique called "magnetic curvature analysis" (MCA) (Shen *et al.* 2003) by expanding a curvature $\mathbf{C} = \partial\mathbf{b}/\partial S = \mathbf{b}\cdot\nabla\mathbf{b}$, where $\mathbf{b} = \mathbf{B}/|\mathbf{B}|$ is the unit magnetic field and S is the arc-length, into $C_j = B^{-2}\Sigma_i B_i \nabla_i B_j - B^{-4} B_j \Sigma_{i,k} B_i B_k \nabla_i B_k$, where i, j, k label Cartesian coordinates $\{x, y, z\}$. A scale of the structure can be estimated from a curvature radius $R_c = 1/|\mathbf{C}|$. Truncation errors of the technique is of order $(a/D)^2$, where a is the spacecraft separation and D is the scale size of the structure (R_c). Motivated by the

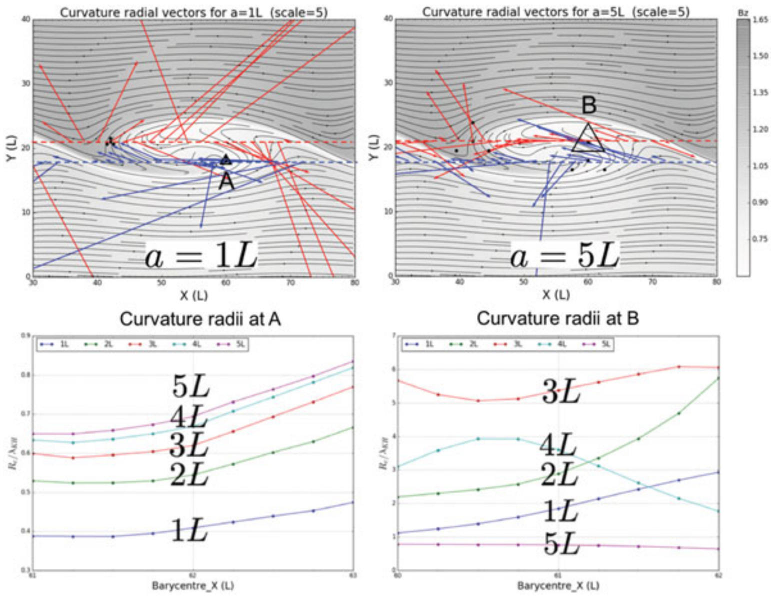

Figure 1. Measures of magnetic curvature on the KH wave by virtual spacecraft. (top) Curvature radial vectors on magnetic contours at two Y-locations from the small (left) and large (right) tetrahedron configurations. (bottom) Curvature radii from the varying tetrahedron sizes with the barycentre at A and B labeled in top panels.

curved, vortical structures of KH waves, we aim to apply the MCA on simulated KH waves to consider applications in real data.

2. Numerical Simulation and Analysis

We simulate the KH instability using Lare2d which is a resistive MHD code in 2.5D (Arber *et al.* 2001). The simulation reproduces KH waves for typical conditions along the Earth's flank magnetopause on the duskside in GSM coordinates. Magnetic field, ion density, ion temperature, and ion speed are modelled with hyperbolic tangent profiles with asymptotic values of the magnetosheath and magnetospheric sides as in Otto and Fairfield, (2000). The KH wavelength is $\lambda_{KH} = 40L$, where $L = 600$ km. We set up virtual probes, to sample across the simulation plane, in a regular tetrahedron configuration and vary the separation at typical *Cluster* scale-sizes $a = [1L, 5L]$.

Figure 1 shows measures of magnetic curvature along the X-direction of a time snapshot of the non-linear KH waves at two Y-locations. The top panels show a comparison between small ($a = 1L$, left) and large ($a = 5L$, right) tetrahedron results. Curvature radial vector projections $\mathbf{R_c} = R_c\mathbf{c_x} + R_c\mathbf{c_y}$ are plotted on magnetic field maps, with components B_z in grey and B_x, B_y as contours. Each curvature radial vector points from the tetrahedron barycentre in the direction of magnetic tension force. The small tetrahedron results show that the curvatures roughly point against the flow direction in the KH vortex (towards -X for the top cut and towards +X for the lower cut), consistent with distortion of the magnetic fields induced by the vortical flow. The large tetrahedron results, in contrast, show different curvatures, in both magnitudes and directions. In the lower panels, we further examine curvature radius for the varying tetrahedron sizes at chosen location ranges, labeled as A and B in top panels. The barycentres at A and B are in range X=[61, 63] and X=[60, 62] respectively. At location range A, the curvature

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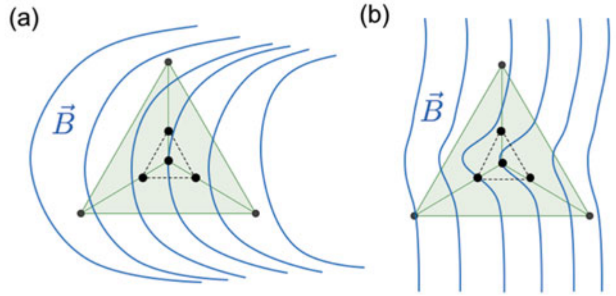

Figure 2. Measures of curvature in magnetic field structures by nested spacecraft of small (dashed) and large (shaded) tetrahedron size. The magnetic field structures have spatial variations/non-zero curvature at (a) large and (b) small scales. Adapted from Kieokaew *et al.* (2018).

radius increases as the tetrahedron size increases, showing that a larger tetrahedron resolves a larger structure. At location range B, in contrast, the lowest curvature radius is found by the largest tetrahedron $a = 5L$ while the highest radius is found by the medium size tetrahedron $a = 3L$. This shows a complex dependence on the tetrahedron size.

3. Discussions and Summary

The variations of the MCA results regarding the tetrahedron size may result from spatial variations in the magnetic structures or from limitations of the technique. Figure 2 illustrates two scenarios of magnetic field structures that lead to the results in Figure 1: those with high spatial variations at (a) large scale and (b) small scale. As the tetrahedron size increases, the scenarios would lead respectively to (a) decreasing and (b) increasing radius of curvature. The scenario (b) provides a plausible explanation for the results at location range A in Figure 1, where the curvature radius is increasing with the tetrahedron size. Combinations of both scenarios would result in the complex dependence on the tetrahedron size in location range B: the magnetic structure is consistent with the scenario (b) in the small to medium scales (1L to 3L) while it is consistent with the scenario (a) in the large scales (4L to 5L).

The MCA technique has been applied in a simulation of KH waves using varying tetrahedron sizes. The technique has revealed the magnetic distortion, useful for future analyses with real data, i.e., for identifying characteristic regions of KH waves. Magnetic curvature radius and direction vary depending on the sizes of the tetrahedron, possibly due to spatial variations in the magnetic structures. Such plasma structures with non-linear spatial variations are common in space and would be best observed by nested, cross-scale four-spacecraft. Further details of this study on magnetic curvature and complementary analysis on vorticity can be found in Kieokaew *et al.* (2018).

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