Kelvin-Helmholtz Multi-Spacecraft Studies at the Earth's Magnetopause Boundaries

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Abstract. The Kelvin-Helmholtz (KH) instability can operate in various situations in the solar wind, but at the boundaries of planetary obstacles, for example the Earth's magnetopause, it is most amenable to investigation. Reliable estimates of wave characteristics are essential for comparison with theoretical and numerical models and for understanding the non-linear development of KH waves and their role in the plasma entry into the magnetosphere. After discussing their typical conditions of appearance in KH unstable domains at the magnetopause, both theoretically and observationally, we outline recent results of multi-spacecraft analysis with Cluster giving accurate, albeit spatially limited, determination of surface wave characteristics. Those characteristics (wavelength and propagation direction), close to the terminator on the nightside, are likely to be prescribed by the 3-D geometry and the bending of field lines developed by the KH waves, rather than by the magnitude and the direction of the magnetosheath or background flow. An unprecedented number of satellites provides now the opportunity to extend the analysis of source regions of KH waves and their domains of development.

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INTRODUCTION

The Kelvin-Helmholtz (KH) instability is a classical example of flow-driven instability, which plays a major role in solar or extrasolar system phenomena such as coronal dynamics, the magnetospheric and heliospheric boundaries and cometary tails, and in astrophysical jets. For example, in the solar wind, it is one of the possible mechanisms responsible for Alfvénic fluctuations, generated by shear flows across tangential discontinuities [1]. However, the most favorable region in space for its multipoint in-situ observation and analysis is by far the outer boundary of the Earth's magnetosphere – the magnetopause – and its adjacent boundary layers [*e.g.* 2, 3, 4].

The KH mechanism at the magnetopause contributes to the widening of the the low latitude boundary layer (LLBL) [5]. The result was demonstrated during Northward IMF conditions from multi-spacecraft analysis with *Cluster* [4]. The LLBL is a mixing layer adjacent to and Earthward of the magnetopause at low geomagnetic latitudes, with densities and velocities intermediate between values in the magnetosheath and the magnetosphere proper. However, it is not clear when, and to what extent, the KH mechanism generates the observed LLBL properties, since it may have to compete with, or enhance, other mechanisms. The LLBL properties may result, for example, from diffusion onto closed field lines [*e.g.* 6] or reconnection of interplanetary and geomagnetic fields [*e.g.* 7]. Both particle transport mechanisms may operate in KH vortices, which may then carry the mixed plasma over large distances down the tail [8]. The KH instability is also believed to be operative in other planetary environments of the solar system [*e.g.* 9].

For these reasons, reliable estimates of the wave characteristics are essential, notably via comparison with theoretical and numerical models, to elucidate the conditions leading to the formation of KH waves, their possible non-linear development and their role in the plasma entry into the magnetosphere. Focusing on the KH waves at the magnetopause, we first discuss their typical conditions of appearance. We then outline recent results of multi-spacecraft analysis with *Cluster* giving accurate, albeit spatially limited, determination of surface wave characteristics. We conclude on what recent broad multi-spacecraft configurations can provide to shed further light on the KH mechanism.

KH UNSTABLE DOMAINS

KH waves are commonly understood as surface waves, characterised by a rapid spatial decay away from both sides of the interface. In the simplest linear magnetohydrodynamic (MHD) description, the onset condition for the KH instability in an ideal incompressible plasma, with a discontinuous velocity shear layer and assuming the layer to be infinitely thin (*i.e.* in the limit of no bound-

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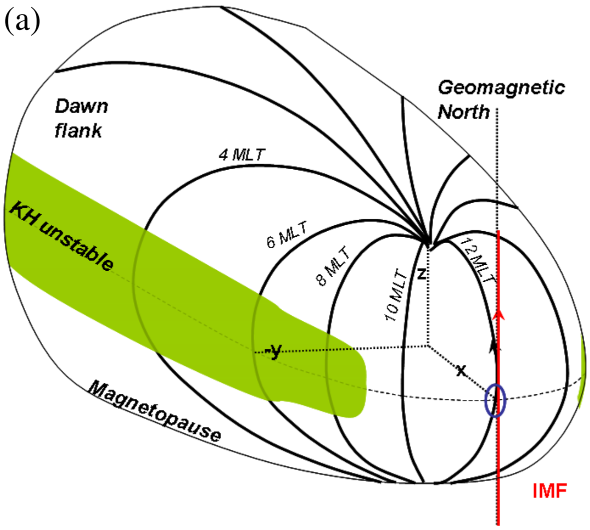

FIGURE 1. View of the magnetopause and adjacent geomagnetic field from a dayside and North-West vantage point. The distribution in green of KH unstable regions is given for maximum KH growth rates above a 0.1 threshold as obtained without boundary layer [2] for northward IMF with (a) zero IMF clock angle and (b) an IMF clock angle (indicated by a blue arc) of -30°. Slightly reduced growth rates are obtained in the presence of the boundary layer. The regions of instability represented on the nightside are an extension (downtail) of the regions that are validated by simulation results [2] on the dayside. In case (b), the position of *Cluster* on the dawn flank is indicated by a red filled circle.

ary layer or long wavelengths) [10], is

$$[\mathbf{k}.(\mathbf{V_1}-\mathbf{V_2})]^2 > \frac{n_1+n_2}{\mu_0 m_p n_1 n_2}\left[(\mathbf{k}.\mathbf{B_1})^2+(\mathbf{k}.\mathbf{B_2})^2\right] . \quad (1)$$

Here the indices refer to the two plasma environments on either side of the boundary, n is the plasma number density, m_p the proton mass, μ_0 the permeability of free space, **V** is the plasma flow velocity, **B** the magnetic field vector and **k** the wave vector; **V**, **B** and **k** are all locally tangential to the layer. As Equation (1) shows, KH waves are caused by a velocity gradient or shear, $|\mathbf{V_1}-\mathbf{V_2}|$, between the streaming magnetosheath and relatively stagnant magnetospheric plasmas, in the case of the magnetopause. The instability criterion is more likely to be met for wave propagation in the direction of high flow shear. Moreover, the threshold above which KH instability may occur (*i.e.*, the right-hand-side in Equation (1)) is reduced in the regions of low or high magnetic shear between the magnetosheath and magnetospheric field lines (when $\mathbf{B_1}$ and $\mathbf{B_2}$ are respectively parallel or anti-parallel) and for wave propagation perpendicular to the magnetic fields: this part corresponds to stabilising effects from magnetic tension forces [e.g. 11] that are weakened for strongly northward or southward IMF (*i.e.* low or high magnetic shear respectively).

Velocity shear induces the onset of the KH instability, but the 3-D topology and various conditions of the magnetised plasma introduce additional constraints and control the characteristics of the resulting disturbances. Much insight has been gained by performing idealised high-resolution numerical simulations, where e.g. the role of the initial magnetic topology in the decay to magneto-turbulence became evident [13]. The KH instability leads to the compression of field lines in localized zones, which in turn, leads to reconnection driven by the flow [*e.g.* 14]. The analysis of resistive instabilities and magnetic reconnection requires high order spectral-like techniques where the diffusion coefficients may be controlled explicitly. In addition, the Hall term, electron inertia and kinetic effects (such as wave-particle interactions) introduce dispersion and increase the number of wave-modes. At the magnetopause in particular, MHD simulations [8] indicate that reconnection can occur inside the narrow current layers generated by the KH instability. When the magnetic fields are initially anti-parallel over the velocity shear layer, 2-D Hall-MHD numerical simulations [*e.g.* 15] show that reconnection can operate in two regions within the vortex: a) in the current layer separating magnetosheath and magnetospheric fields and b) in the current layer generated by the twisting of the KH vortices.

Furthermore, due to the 3-D geometry of the magnetopause surface, there is a finite interaction region with the interplanetary magnetic field lines at which the KH instability can operate without being stabilised by the field line curvature and tension. The size of this KH unstable domain may set an upper limit for the KH wavelength [2, 4]. Figure 1 illustrates the relation between the regions satisfying the conditions for the KH instability onset, *i.e.* wave activity generation, and the IMF clock

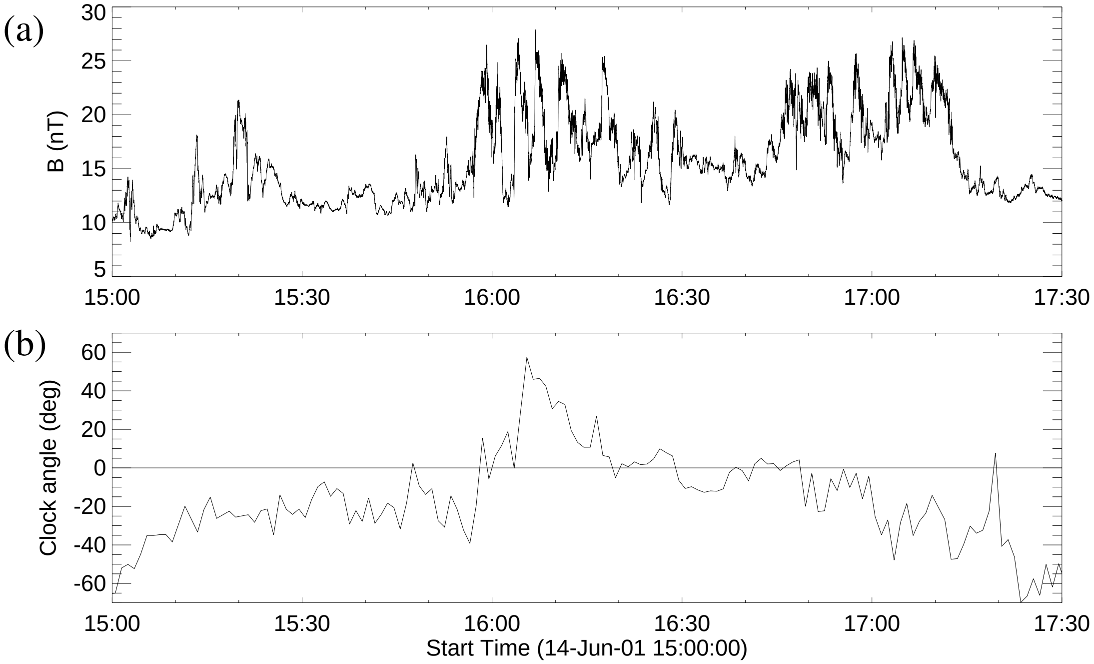

FIGURE 2. The occurence of magnetopause surface waves on 14 June 2001 between 15:00 and 17:30 UT, (a) shown in the magnetic field magnitude $|B|$ from the Flux Gate Magnetometer (FGM) on *Cluster* C2: the magnetosheath plasma is associated with $|B| \sim 25$ nT, while inside the magnetosphere $|B| \sim 15$ nT [after 12]; (b) related to the IMF clock angle, on average -15°in this 2.5-hour time interval, as shown in 1-min running averages inferred from the High Resolution OMNI (HRO) data product (readily time-shifted to a model bow shock nose location), time-shifted by 13 minutes to represent conditions near and upstream of *Cluster*.

angle, defined as the polar angle of the IMF direction in the Geocentric Solar Magnetospheric (GSM) YZ plane. This figure is adapted from [2], who performed linear MHD simulations of the incompressible surface mode disturbances on a mesh covering the dayside of a model magnetopause. Regions of maximum KH growth rates on the dayside magnetopause correspond, as expected, to regions of high flow shear and low magnetic shear. The wave perturbations may become unstable away from the stagnation point in the direction of high flow shear. For small clock angle, the regions of maximum KH growth rates are broad and confined to the equator away from the sunward side (Figure 1a). As the clock angle increases in absolute value (the case of negative clock angle is represented in Figure 1b), the regions of instability narrow and migrate away from the equator, southward on one flank and northward on the other, depending on the sign of the clock angle. Recent 3-D numerical simulations [16] show strong reconnection processes at the boundaries of the KH unstable domain, strongly enhanced plasma transport and, critically, the impact of the 3-D geometry on the wavelength of unstable modes, such that can be unveiled by changes in IMF clock angle [2, 4].

Figure 1b and Figure 2 complement the analysis of the event of 14 June 2001 reported with *Cluster* [12]. Together they show that *Cluster* at position $[-5.5, -16.2, -4.7]$ R_E (GSM), $\sim$ 4.7 MLT and $-15°$GSM latitude, is in a favorable location, with an IMF clock angle of $\sim -15°$, for the occurence of KH waves. This complementary diagnostic supports the interpretation of the surface waves in terms of KH waves for this event. The KH unstable domains in Figure 1b mirror the ones shown for the event of 21 November 2001 on the dusk flank, with small positive IMF clock angle [4, Figure 1].

WAVE CHARACTERISTICS

Quoted values of surface wave observations on the magnetopause indicate that their frequencies are typically in the Pc5 (1-10 mHz) range, with a wide range of phase velocities (varying from about 60 $\mathrm{km\,s^{-1}}$[see 4] to 350 $\mathrm{km\,s^{-1}}$[see 17]) and a similar spread in wavelengths (from 2 R_E [see 4] to a few tens of R_E [see 18]). Arguably, a key factor controlling the wavelengths, λ, is the distance of the observing site from the subsolar point, because the magnetosheath flow speed picks up as one moves tailward, leading to a λ-stretching effect. In addition, KH surface waves in the magnetospheric context can become non-linear while propagating down the tail. Non-linear effects have been invoked to account for (i) wavelengths of a few R_E typically observed on the magnetopause, which, as argued in [19], are much longer than those predicted by linear theory; (ii) the tailward steepening of the KH leading fronts observed with *Cluster* [12, 4], consistent with the growing phase of KH waves [20] (note that the inverse dependence found between the boundary layer thickness and the tailward steepening of the leading edge [4] suggest that this effect is affected by changing conditions of the medium in which the waves propagate); (iii) the presence of vortices, a phenomenon supported by the interpretation of data in single or multi-spacecraft analyses [18, 21, 22, 23]; (iv) an inverse dependence between the IMF clock angle and the wavelength at the flank [4] or the geomagnetic pulsation period [3], which confirms the significance of source regions and non-linear development for interpreting observations of remotely generated KH waves.

Reliable estimates of the wave characteristics are thus essential. Triangulation or 4-spacecraft timing analysis [24] has been applied to our knowledge in two *Cluster* studies of surface waves, that by Owen et al. [12] and that by Foullon et al. [4], on the dawn and dusk flanks respectively. The waves studied have a sawtooth shape, which they retain as they propagate past *Cluster* (within a relatively short time interval), at an epoch when the four satellites have separations of $\sim$2000 km. Such conditions are appropriate for estimating their phase speeds, and consequently their wavelengths, via the method proposed by Foullon et al. [4] [see illustration in 25, and also a more approximative variant in 7]. This method uses aggregate results from 4-spacecraft timing analysis applied to a pair of bounding surfaces as input.

Both *Cluster* studies of surface waves [12, 4] refer to similar distances from the subsolar point (with spacecraft located at $X_{GSM} \approx [-3, -6]$ $\mathrm{R_E}$, on opposite sides of noon and at low geomagnetic latitudes) and indicate phase speeds (50-90 $\mathrm{km\,s^{-1}}$) and wavelengths (2-3.4 $\mathrm{R_E}$) in the lower range compared to other reports in the same locales. Although they represent a modest sample of the observations analysed over the past, the phase speeds derived so far with *Cluster* yield values of a 1/3 or less of the magnetosheath flow speed ($\sim$260 $\mathrm{km\,s^{-1}}$in [4]) or the average flow speed in the boundary layer ($\sim$200 $\mathrm{km\,s^{-1}}$in [4, Figure 4c]). Both *Cluster* studies also refer to locales south of the equatorial plane, but the directions of wave propagation are found to have either a southward [4] or a northward [12] component. Rather than being related to the magnetosheath flow component (expected to be southward in both cases, although without marked evidence for it [see 4, Figure 4g]), the direction of propagation is perpendicular to an average external magnetic field direction, as expected when generated by the KH mechanism. The unexpected field direction in [12] may result from the bending of field lines by the KH waves [see also 4].

CONCLUSIONS

Although shear flows are essential for the KH instability to occur, the KH wave characteristics (wavelength and propagation direction) may initially, close to the terminator on the nightside, have little to do with the magnitude and the direction of the flow itself. The impact of 3-D geometry may set an upper limit for the initial wavelength of unstable KH modes, which may then develop non-linearly along the flank. The wave propagation direction may adjust to the bending of field lines developed by the KH waves. Accurate, albeit spatially limited, determination of surface wave characteristics with *Cluster* comply with this theory. To characterise the evolution of the KH activity with changes in interplanetary and local conditions and along the flank magnetopause, an unprecedented number of satellites is now or has recently been crossing the Earth's magnetospheric boundary in concert, repeatedly and in different places (the 4 *Cluster*, the Double Star TC-1 satellite and other spacecraft such as *Geotail* and the 5 THEMIS spacecraft). In favourable configurations, these spacecraft are separated from each other by several Earth radii along the flank magnetopause. They provide the opportunity to extend the analysis of source regions of KH waves and their domains of development.

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