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# North-South asymmetric Kelvin-Helmholtz instability and induced reconnection at the Earth's magnetospheric flanks

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#### 8 Abstract

We present a three-dimensional study of the plasma dynamics at the flank magnetopause of 9 the Earth's magnetosphere during mainly northward interplanetary magnetic field (IMF) pe-10 riods. Two-fluid simulations show that the initial magnetic shear at the magnetopause and 11 the field line bending caused by the dynamics itself (in a configuration taken as represen-12 tative of the properties of the flank magnetopause) influence both the location where the 13 Kelvin-Helmholtz (KH) instability and the induced magnetic reconnection take place and 14 their nonlinear development. The KH vortices develop asymmetrically with respect to the 15 Earth's equatorial plane where the local KH linear growth rate is maximal. Vortex driven re-16 connection processes take place at different latitudes, ranging from the equatorial plane to 17 mid-latitude regions, but only in the hemisphere that turns out to be the less KH unstable. 18 These results suggest that KH-induced reconnection is not limited to specific regions around 19 the vortices (inside, below or above), but may be triggered over a broad and continuous range 20 of locations in the vicinity of the vortices. 21

#### 1 Introduction

The large-scale dynamics of the Earth's magnetosphere can be modelled, as a first ap-23 proach, adopting a one-fluid magnetohydrodynamic (MHD) description. In fact the magne-24 tospheric plasma follows an "ideal" dynamics over most of its spatial domain, the magnetic 25 field lines being frozen into the plasma motion and any cross-field diffusion being fairly neg-26 ligible [Sonnerup, 1980; Labelle and Treumann, 1988; Le et al., 1994]. The magnetospheric 27 region where field lines are "anchored" to the Earth is separated from the heated solar wind 28 plasma of the magnetosheath, where the interplanetary magnetic field (IMF) lines are con-29 nected to the open space, by a magnetic boundary known as the magnetopause. 30

Independently of its complex magnetic shape, in the absence of cross-field diffusion the frozen-in law prevents any kind of mixing between the magnetospheric and the solar wind plasmas. Therefore the plasma of solar wind origin could not in principle enter into the less dense magnetosphere.

However, the frozen-in condition can be locally violated by non-ideal effects arising at small scales generated by the plasma dynamics itself, e.g. allowing for magnetic reconnection to occur. Since reconnection is capable of modifying the global magnetic field topology, it strongly impacts both the dynamics of the whole system and the transport properties at the

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magnetopause. In particular during southward periods when the IMF direction is opposite to that of the magnetospheric magnetic field at low latitude, reconnection occurs at dayside magnetopause allowing for direct transport across the magnetopause and leading to the formation of a low-latitude boundary layer (LLBL) where solar wind and magnetospheric plasmas can mix [*Dungey*, 1961].

<sup>44</sup> During northward periods the magnetic configuration at the low latitude magnetopause <sup>45</sup> is unfavourable for magnetic reconnection to occur. Nevertheless the formation of a LLBL is <sup>46</sup> observed also during these periods [*Mitchell et al.*, 1987] up to the point that the entry of so-<sup>47</sup> lar wind particles into the magnetosphere can be even more important than during southward <sup>48</sup> periods [*Terasawa et al.*, 1997]. Different mechanisms have been invoked for explaining this <sup>49</sup> transport which is routinely observed by satellites.

The non linear vortex dynamics resulting from the development of the Kelvin-Helmholtz 50 (KH) instability is one of the few phenomena, together with lobe reconnection [Gosling 51 et al., 1991; Song and Russell, 1992; Onsager et al., 2001] and kinetic Alfvén waves [John-52 son et al., 2001; Johnson and Cheng, 2001; Chaston et al., 2007], able to explain the ob-53 served transport (see, e.g., Faganello and Califano [2017] for further details on the respective 54 role of the different phenomena). The KH instability is driven by the velocity shear between 55 the stagnant magnetosphere and the flowing magnetosheath plasma of solar wind origin and 56 grows along the magnetospheric flanks at low latitude, where the stabilizing magnetic shear 57 is weaker for northward IMF. By contrast, under such northward IMF conditions, higher lati-58 tude regions are instead completely stabilized by the stronger magnetic shear. 59

Per se, the KH vortices developing during the non-linear phase can strongly perturb the 60 magnetopause but cannot mix the two different plasmas as their typical scale is so large that 61 their early dynamics remains "MHD-ideal". However, they become the driver of very fast 62 secondary instabilities which give rise to a rich, small-scale non-linear dynamics that feeds 63 on the energy source provided by the vortical motion: from secondary Kelvin-Helmholtz 64 and Rayleigh-Taylor instabilities [Matsumoto and Hoshino, 2004; Faganello et al., 2008a; 65 Tenerani et al., 2011; Nakamura and Daughton, 2014], to magnetic reconnection [Knoll and 66 Brackbill, 2002; Nakamura et al., 2006; Otto and Fairfield, 2000; Faganello et al., 2008b, 67 2012a], magnetorotational instability [Matsumoto and Seki, 2007] or current-sheet kink in-68 stability [Nakamura et al., 2004]. 69

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If a magnetic shear exists across the low-latitude magnetopause, the KH velocity field 70 will eventually pinch the magnetopause current sheet in between vortices and force the so-71 called "Type I" vortex induced reconnection to occur there [Liu and Hu, 1988]. In this case 72 reconnection must proceed on nearly the same ideal time-scale of the vortex dynamics in 73 order to release the magnetic energy that piles-up at the compressed current sheet carried 74 by the ideal motion [Chen et al., 1997; Knoll and Brackbill, 2002; Nakamura et al., 2006, 75 2013]. Type I reconnection creates field lines that thread through the magnetopause, leading 76 to a direct entry of solar wind particle into the magnetosphere. 77

If the initial magnetic shear is set to zero and high-latitude KH stable region are included in the model, it has been shown that reconnection develops first at mid-latitude instead of around the equatorial plane where the vortices are generated by the primary KH instability. This process is driven by the braiding and the stretching of the field lines advected by the vortices at the equator but remaining anchored at higher latitudes in the Earth's magnetosphere [*Faganello et al.*, 2012a, 2014].

Under such conditions, mid-latitude reconnection develops almost symmetrically with respect to the equatorial plane and creates double-reconnected flux tubes. These newly closed flux tubes, located on the Earthward side of the magnetopause, thus become populated with dense solar wind plasma. In this way, solar wind plasma enters the magnetosphere at a rate that is compatible with the observed one [*Faganello et al.*, 2012a].

Recently, MMS spacecraft data have provided unambiguous in situ evidence of mag-89 netic reconnection which were interpreted as Type I reconnection at the compressed current 90 sheets forming in between primary successive KH vortices [Eriksson et al., 2016], confirm-91 ing past observations with Cluster [Nykyri et al., 2006; Hasegawa et al., 2009]. Remarkably, 92 for the same MMS event evidences were also found for remote reconnection [Vernisse et al., 93 2016], i.e. occurring far away from the satellite location, as signalled by heated ions and 94 electrons flowing parallel and anti-parallel along magnetic field lines just outside the mag-95 netopause (e.g. Gosling et al. [1991]; Fuselier et al. [1995]; Lavraud et al. [2006]. These 96 results suggest that Type I and mid-latitude reconnection coexist and cooperate in forming 97 the LLBL for northward IMF, when a magnetic shear is present. 98

Here we present a numerical study that takes into account both a pre-existing shear be tween the magnetospheric field and the IMF, as well as the high-latitude stabilization of the
 KH instability, allowing for the simultaneous development of Type I and mid-latitude recon-

-4-

nection. In Sec. 2 we present the plasma model, the initial equilibrium and the parameters

used in our simulations. In Sec. 3 we show how the large-scale structures of the vortices are

<sup>104</sup> modified when both magnetic shear and high-latitude stabilization are present. In Sec. 4 we

<sup>105</sup> present the analysis of the KH-induced reconnection processes. Finally, in Sec. 5 conclu-

sions are drawn.

#### 107

#### 2 Plasma model and simulation setup

We adopt a Hall-MHD plasma model (including finite resistivity). The model equations, in conservative form, are:

$$\partial_t n + \nabla \cdot (n\mathbf{u}) = 0 \tag{1}$$

$$\partial_t (n\mathbf{u}) + \nabla \cdot \left( n\mathbf{u}\mathbf{u} + P_{tot} \overline{\overline{\mathbf{I}}} - \mathbf{B}\mathbf{B} \right) = \mathbf{0}$$
<sup>(2)</sup>

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$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E} \tag{3}$$

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \mathbf{J}/n \times \mathbf{B} - \nabla P_e / n + \eta \mathbf{J}$$
<sup>(4)</sup>

where all quantities are normalized to ion (proton) quantities, the ion mass  $m_i$ , the inertial length  $d_i$  and the Alfvèn speed  $v_A$ . Here *n* is the plasma number density,  $\mathbf{u} \simeq \mathbf{u}_i$  the fluid velocity and  $P_{tot} = P_i + P_e + B^2/2$ . The ion and electron thermal pressures are evolved following an ideal adiabatic closure:

$$\partial_t (nS_{i,e}) + \nabla \cdot \left( nS_{i,e} \mathbf{u}_{i,e} \right) = 0 \quad ; \quad S_{i,e} = P_{i,e} n^{-5/3} \tag{5}$$

#### <sup>117</sup> Finally, we neglect the displacement current; then, the Faraday equation and the electron

fluid velocity are given by

$$\mathbf{J} = \nabla \times \mathbf{B} \quad ; \quad \mathbf{u}_e = \mathbf{u} - \mathbf{J}/n \tag{6}$$

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With this model, during the initial large-scale dynamics leading to the formation of 123 fully rolled-up KH vortices, the magnetic field is frozen into the ion fluid motion and the dy-124 namics is correctly described by ideal MHD. During this phase the system spontaneously 125 starts to distort and shrink the initial current sheet, eventually reaching a characteristic width 126 comparable with the ion inertial length  $d_i$ . As a result, where the magnetic configuration is 127 favourable, Hall-reconnection sets in on a fast time scale [Birn et al., 2001; Faganello et al., 128 2008c, 2012a]. Admittedly, our model neglects the kinetic dynamics at scales smaller than 129 d<sub>i</sub>, as well as possible anisotropy effects [see, e.g., Cerri et al., 2013; De Camillis et al., 130

2016, and references therein]. Nevertheless, when implemented for reproducing a large por-131 tion of the boundary our model can realistically evaluate reconnection-induced plasma ex-132 changes at the magnetopause [see Henri et al., 2013]. Indeed we are not interested in the 133 kinetic details of the reconnecting structures, such as ion and electrons exhausts, particle ac-134 celeration or particle streaming along newly reconnected lines but on the modification of the 135 global magnetic topology during the KH evolution. For this purpose a Hall-MHD descrip-136 tion is sufficient since it is able to catch the correct reconnection rate and thus to describe 137 correctly the modifications of the global topology during the time-evolving configuration 138 created by the KHI. 139

The model equations are integrated numerically using a  $4^{th}$  order Runge-Kutta scheme. Spatial derivatives are calculated using  $6^{th}$  order explicit finite differences along the periodic *y* and *z* directions, while a  $6^{th}$  order implicit compact scheme with spectral-like resolution [*Lele*, 1992] is adopted along the inhomogeneous *x*-direction. Very short wavelength fluctuations are dissipated using high order spectral filters acting only on the high-k part of the spectrum [*Lele*, 1992].

Special care is devoted to the boundaries along the inhomogeneous x-direction where 146 we adopt transparent conditions for any MHD alfvénic or sonic perturbation generated inside 147 the numerical domain. This method is based on projected characteristics of the ideal-MHD 148 set of equations allowing one to control the in/out flux at the boundaries [Hedstrom, 1979; 149 Thompson, 1990; Landi et al., 2005; Faganello et al., 2009]. In order to deal with the non-150 ideal MHD terms of our set of equations, such as the Hall and the diamagnetic terms in the 151 Ohm's equation, we gradually smooth them out in a buffer regions close to the boundaries. 152 We set the boundaries far enough from the central region where small-scale structures de-153 velop during the dynamics and where non-ideal effects are thus important. Thus, we do not 154 observe any spurious reflection neither at the boundaries nor in the buffer regions. 155

Simulations are initialized starting from a 2D ideal MHD equilibrium taken as uniform along the flow direction (*y*-coordinate). The *x* and *z* axis are set perpendicular to the unperturbed magnetopause and along the northward direction, respectively. In this configuration all equilibrium quantities are functions of  $\psi$  only, where  $\psi = \psi(x, z)$  is a magnetic flux function satisfying the Grad-Shafranov equations [*Andreussi et al.*, 2012; *Faganello et al.*, 2012a,b].

$$\Delta \psi = \frac{d}{d\psi} \Pi \quad ; \quad \Pi = P_{0,i} + P_{0,e} + B_{0,y}^2 / 2 \tag{7}$$

Setting  $\Pi = cst$  a simple solution is given by

$$\psi_0(x,z) = \frac{1+\delta}{2}x + \frac{1-\delta}{2}\frac{L_z}{2\pi}\sinh\frac{2\pi x}{L_z}\cos\frac{2\pi z}{L_z}$$
(8)

<sup>163</sup> while the other equilibrium quantities are set as

$$n_0 = 1 \tag{9}$$

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$$\mathbf{u}_0(x,z) = \frac{u_{\star}}{2} \tanh \frac{\psi_0(x,z)}{\ell_{\star}} \,\mathbf{e}_y \tag{10}$$

$$\mathbf{B}_0(x,z) = \nabla \times \psi_0(x,z)\mathbf{e}_y + \frac{\tan(\varphi)}{2} \left[1 + \tanh\frac{\psi_0(x,z)}{\ell_\star}\right] \mathbf{e}_y \tag{11}$$

where  $\varphi$  is the shear angle between the magnetospheric field and the IMF. The first term in Eq. (11) corresponds to the northward magnetospheric field (x < 0) and the dominant northward component of the IMF (x > 0). The second term adds a flow aligned component to the IMF, taking into account possible different configurations that are observed during periods of northward IMF. The equilibrium thermal pressure  $P_{0,i} + P_{0,e}$  is the dominant term in II and varies from the magnetosphere to the magnetosheath in order to compensate for the increasing of  $B_{0,v}^2/2$ . A sketch of this equilibrium configuration is given in Fig. 1.

In our simulations we set  $L_z = 120\pi$  and  $\delta = 1/3$  so that the northward component 173 of the magnetic field is nearly straight inside within the interval  $-L_x/2 < x < L_x/2$ , with 174  $L_x = 90$ . Setting  $\ell_{\star} = 3 \ll L_x$  we obtain an equilibrium configuration that varies mainly 175 along the x-direction and a velocity shear layer vorticity at x = 0 that is three times larger 176 at z = 0 than at  $z = \pm L_z/2$ . As a consequence the KH instability, whose maximal growth 177 rate is a fraction of the velocity shear layer vorticity [Drazin and Reid, 1981], develops far 178 faster in the equatorial region than at higher latitudes. This initial 2D configuration permits 179 to mimic the preferential equatorial development of the KH instability at the flank magne-180 topause, under northward IMF. In the case of the Earth's magnetosphere, however, stabi-181 lization at higher latitudes is expected and observed owing to magnetosheath flow and mag-182 netic field draping properties, so that magnetic and flow fields become more aligned and thus 183 less prone to KH development [Chandrasekhar, 1961]. The box dimension along the flow is 184  $L_y = 2\lambda_{FGM,z=0} = 30\pi$ , where  $\lambda_{FGM,z=0}$  is the expected wavelength of the fastest growing 185 mode as given by a simplified 2D stability analysis at the equatorial plane. The number of 186 grid points along each direction is given by  $n_x = 900$ ,  $n_y = 512$ ,  $n_z = 512$ . 187

The sonic and alfvénic Mach number are defined as  $M_s = u_{\star}/c_s$  and  $M_A = u_{\star}/v_{A,z}$ , where  $c_s$  and  $v_{A,z}$  are calculated at at the centre of the numerical box. Their values, together with the other parameters, are listed in table 1. Finally, we take  $P_i = P_e$  and  $\eta = 0.001$ .

run	$M_A$	$M_s$	$tan(\varphi)$	description
"A"	1.0	$\sqrt{3/5}$	0.3	weak magnetic shear
"B"	2.0	$\sqrt{12/5}$	1.0	strong mag. shear & high velocity

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 Table 1.
 Summary of the relevant parameters characterizing the different simulations.

In order to follow the system evolution, to individuate the plasma structures forming during the dynamics and to follow the field line connectivity, we define a passive tracer  $\varsigma$ advected by the fluid so as to mark the two different plasmas during the evolution. At the beginning of the simulation the passive tracer is set as

$$\varsigma(x,z) = 0.6 + 0.4 \tanh\left[\frac{\psi_0(x,z)}{\ell_{\star}}\right]$$
 (12)

where  $\varsigma < 0.6$  corresponds to the magnetospheric plasma and  $\varsigma > 0.6$  to the solar wind one while  $\varsigma \simeq 0.6$  determines the position of the magnetopause. The passive tracer  $\varsigma$  is constant along each magnetic field line and evolves as the field lines would do within ideal MHD. In this way  $\varsigma$  allows us to identify the reconnected lines linking the magnetospheric and solar wind plasma as those along which a variation of  $\varsigma$  is measured.

#### <sup>201</sup> 3 Large-scale dynamics of KH vortices

#### 202

#### **3.1** Overview of the dynamics

As expected, from the initial white noise perturbation KH waves emerge around the wavelength associated with the fastest-growing mode (FGM) as predicted by linear theory. Given the length of the numerical box, two vortices appear at the end of the linear phase (not shown here). As soon as they enter the non-linear phase the pairing process starts [*Winant and Browand*, 1974; *Miura*, 1997]. As a result the vortices eventually merge generating a single larger vortex.

In Fig. 2 we show the passive tracer iso-contours at t = 460 for run "B". For sake of clarity, the box has been doubled along the *y*-direction so that two pairs of coupling vortices appear instead of one. The semi-transparent quasi-vertical iso-surface corresponds to the magnetopause,  $\varsigma = 0.6$ , while the dark/light blue colour correspond to the magnetospheric/solar wind plasma.

Two pairing vortices have been produced around the equatorial region, the magne-214 topause being wrapped inside the vortex motions. The vortex structures, as shown by the 215 folded magnetopause, extend both into the north and into the south hemispheres and are 216 tilted with respect to the z-axis, corresponding to a KH wavevector not aligned with the ini-217 tial flow. We recall that in the absence of an initial magnetic shear (tan  $\varphi = 0$ ), the KH vor-218 tex axis would be parallel to the z-axis. As expected for the chosen initial configuration, the 219 vortices grow around the central region of the box while they are stable at high latitudes, as 220 shown by the colour configuration in the unperturbed planes at  $z = \pm L_z/2$ . However, the 221 presence of an equilibrium magnetic shear breaks the reflection symmetry with respect to 222 the equatorial plane of our initial configuration. Indeed while  $\mathbf{u}_0$  and  $B_{0,z}$  are symmetric, 223  $B_{0,y} \rightarrow -B_{0,y}$  for  $z \rightarrow -z$ : the different properties under reflection follow from the fact that 224 the velocity is a vector while the magnetic field is an axial vector. 225

As a consequence, vortices develop differently in the northern and in the southern hemispheres, e.g. preferring the southern hemisphere for  $\tan \varphi > 0$  as shown in Fig. 2 (the opposite is true for  $\tan \varphi < 0$ ). The physical mechanism that favours one hemisphere with respect to the other is the combined action of vortex growth and field line tying at high latitudes as will be discussed next in Sec.3.3.

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#### 3.2 The tilting of unstable modes

The vortex tilting observed in Fig. 2 is the consequence of the presence of a magnetic 236 shear in the equilibrium configuration. This point can be understood as follows. The most 237 unstable modes are the ones able to minimize the magnetic tension proportional to  $\mathbf{k} \cdot \mathbf{B}_0$ 238 (that counteracts the KH development) more than to maximize the driving term proportional 239 to  $\mathbf{k} \cdot \mathbf{u}_0$  (here  $\mathbf{k} = 2\pi m/L_v \mathbf{e}_v + 2\pi n/L_z \mathbf{e}_z$  is the mode wavevector, m and n the mode numbers 240 along y and z). This effect has been proven to be at work when considering 1D equilibria 241 varying only along x [Southwood, 1968; Walker, 1981], but remains efficient also in our 2D 242 equilibria with high-latitude stabilization. Indeed, the most unstable modes underlying the 243 development of the vortex structures have a wavevector oblique with respect to the flow ve-244 locity and it is roughly perpendicular to the magnetic field direction (close to the velocity 245 shear layer). 246

In order to calculate the KH growth rate analytically, we consider the limit where the flow velocity and the magnetic field are uniform in two different regions separated by a sharp

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- discontinuity at x = 0. In our equilibrium configuration this would correspond to the limit
- $\ell_{\star} \to 0$  and  $\delta \to 1$ . By assuming incompressible perturbations, the KH growth rate is given

by [*Chandrasekhar*, 1961]

$$\gamma(k,\vartheta,M_A,\varphi) = k\cos(\vartheta) \left[\frac{M_A^2}{4} - \tan^2\vartheta - \tan\vartheta\,\tan\varphi - \frac{\tan^2\varphi}{2}\right]^{1/2}$$
(13)

where  $\vartheta$  is the angle between the wavevector and the flow direction  $\mathbf{e}_{v}$ . This system is unsta-

ble if and only if  $\vartheta_{-} \leq \vartheta \leq \vartheta_{+}$ , where  $\vartheta_{\pm}$  is defined by

$$\vartheta_{\pm} = \arctan\left[-\frac{\tan\varphi}{2} \pm \frac{\sqrt{M_A^2 - \tan^2\varphi}}{2}\right]$$
 (14)

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Once all the parameters but  $\varphi$  are fixed, the most unstable modes are found for

$$2\vartheta_{\max} = -\arctan\left(\frac{4\tan\varphi}{4-2\tan^2\varphi + M_A^2}\right)$$
(15)

that is different from zero provided that  $\tan \varphi \neq 0$ . For small  $M_A$  and small  $\varphi$  we have  $\vartheta_{\text{max}} \simeq -\varphi/2$ , so that  $\mathbf{k} \cdot \mathbf{B}_0 = 0$  around the center of the velocity shear layer. For large  $\varphi$  the angle  $\vartheta_{\text{max}} < -\varphi/2$  because in our equilibrium configuration the magnitude of  $\mathbf{B}_0$  is bigger in the magnetosheath than in the magnetosphere by a factor  $(1 + (\tan \varphi)^2)^{1/2}$ . For large  $M_A$  the stabilizing effect of the magnetic field is reduced so that the most unstable wavevector tends to be aligned with the flow ( $|\vartheta_{\text{max}}|$  decreases). Note that for  $z \rightarrow -z$ , the magnetic shear angle  $\varphi$  as well as  $\vartheta$  change sign and that  $\gamma(-\vartheta, -\varphi) = \gamma(\vartheta, \varphi)$ .

Even if this model is oversimplified, it yet gives some insights about the tilt angle of 262 oblique modes observed in the 3D compressible simulations starting from 1D equilibria 263 with  $\ell_{\star} \neq 0$  [Nakamura and Daughton, 2014; Adamson et al., 2016]. A moderate dis-264 crepancy between the predicted  $\vartheta_{max}$  and that observed in the simulations is related to the 265 fact that the simplified model underestimates the role of the magnetic field inside the shear 266 layer  $(|x| \leq \ell_{\star})$ , where the mode amplitude is larger, while overestimates its importance 267 in the two asymptotic region ( $|x| \gg \ell_{\star}$ ). This is clearly shown by our simulations where 268 the observed angle of the most unstable modes is slightly smaller than the predicted one. 269 The actual angle, for both run "A" and "B" is closer to  $-\arctan[(\tan \varphi)/2]$  than to  $\vartheta_{max}$ :the 270 most unstable modes tend to develop perpendicular to the magnetic field at the center of the 271 shear layer, minimizing the stabilizing role of the magnetic tension where the velocity shear 272 term is stronger. Note that, at the center of the shear layer (x = 0) the flow aligned com-273 ponent of the magnetic field is given by  $B_{0,y} = \frac{\tan \varphi}{2}$ , so that the angle between **B**<sub>0</sub> and **e**<sub>z</sub> 274

there is not  $\varphi/2$  but  $\arctan[(\tan \varphi)/2]$ . This is why unstable modes develop preferentially 275 at  $\vartheta_{shear} = -\arctan[(\tan \varphi)/2]$ . This is shown in Fig. 3 where we plot the magnitude of 276 the x-averaged Fourier components of  $u_x$  in the (m, n)-plane (m, n are the mode numbers)277 as defined before) for tan  $\varphi = 0.3$  and tan  $\varphi = 1.0$ . For each *m* number the largest am-278 plitude correspond to n < 0, i.e. to a tilted mode. The central region of the most unstable 279 (tilted) modes observed in the simulations (gray strips) is aligned along the direction given 280 by  $\vartheta_{shear} = -\arctan[(\tan \varphi)/2]$  (dashed line), so that  $\mathbf{k} \cdot \mathbf{B}_0 \simeq 0$  at the center of the 281 shear layer. On the contrary  $\vartheta_{max}$  (continuous line) slightly underestimates the tilting. For 282  $\tan \varphi = 0.3$  we have  $\vartheta_{max} \simeq 7^{\circ}$  and  $\vartheta_{shear} \simeq 8^{\circ}$ . For  $\tan \varphi = 1.0$ ,  $\vartheta_{max} \simeq 17^{\circ}$  and 283  $\vartheta_{shear} \simeq 27^{\circ}.$ 284

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#### 3.3 Latitudinal shift of the vortices

<sup>302</sup> Due to the presence of the magnetic shear in the equilibrium configuration the large-<sup>303</sup> scale KH vortices extend asymmetrically with respect to the equatorial plane. In particular, <sup>304</sup> for tan  $\varphi > 0$ , the latitude band affected by the vortex structures shifts southward, below the <sup>305</sup> equatorial plane. As we will discuss later, the opposite is true for tan  $\varphi < 0$ . Qualitatively <sup>306</sup> this vortex shift can be explained by the differential advection of the magnetic field lines with <sup>307</sup> respect to the latitude position.

Differential advection has been discussed in the limit tan  $\varphi = 0$ , i.e. zero magnetic 308 shear, as an important driver for the magnetic field lines dynamics [Faganello et al., 2012a; 309 Borgogno et al., 2015]. Indeed, magnetic field lines embedded in the vortex structures are 310 slowed down in the equatorial region, with respect to their unperturbed motion, since the KH 311 phase velocity is null in our frame. On the contrary they continue to move at the unperturbed 312 magnetosphere/solar wind velocity at high latitudes. As a consequence, magnetic field lines 313 of different origin are stretched and arched in the opposite directions, leading to the forma-314 tion of intense current sheets at mid latitudes where reconnection finally occurs. When an 315 initial magnetic shear is present, differential advection works somewhat differently. At the 316 beginning the KH mode develops symmetrically with respect to z = 0 but as soon as the vor-317 tices start to form, differential advection becomes more and more important and, contrary to 318 the case without magnetic shear, modifies the vortex structure in a different way above and 319 below the equatorial plane. 320

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A sketch of this mechanism is given in Fig. 4 for  $\tan \varphi > 0$ . We see that the initial magnetospheric and IMF lines, initially straight at  $t = t_1$ , are stretched by the differential advection, resulting in magnetic field lines that are increasingly bent at  $t = t_2$  and  $t = t_3$ . As a consequence the magnetic shear is enhanced in the northern hemisphere while it is reduced in the southern one. Since the magnetic shear tends to inhibit the KH instability the location of the maximal growth rate gradually drifts southward. As a result, for  $\tan \varphi > 0$ , the KHI eventually develops faster in the southern hemisphere.

The different evolution of the magnetic shear in the two hemispheres can be quantified 328 by looking at the peaks of electric current  $J = |\mathbf{J}| = |\nabla \times \mathbf{B}|$ . In Fig. 5, top frame, we plot 329  $max_x(\tilde{J}_{m=0}(x,z)) / max_x(J_0(x,z))$  as a function of z for t = 250, 300, 350, up to the beginning 330 of the nonlinear phase. Here  $J_0$  is the magnitude of the equilibrium current while  $J_{m=0}$  is the 331 magnitude of the m = 0 mode of the total current, thus including the nonlinear modification 332 of the equilibrium. It is clear that the m = 0 magnetic shear is amplified in the northern 333 hemisphere while it lowers in the southern hemisphere, explaining the southward shift of the 334 KH unstable region at the beginning of the nonlinear phase. 335

In the present configuration, where the vorticity  $\Omega_0$  associated with the initial sheared flow is along  $+\hat{z}$ , the equilibrium current  $J_0$  points out the hemisphere where the magnetic shear becomes larger. In general (for  $\Omega_{0,z} \leq 0$ ), the symmetry properties of the mechanism described in Fig.4 suggest that differential advection enhances the magnetic shear in the northern hemisphere for  $\Omega_0 \cdot J_0 > 0$ , while the opposite is true for  $\Omega_0 \cdot J_0 < 0$ . As a consequence KH vortices develop more vigorously in the southern/northern hemisphere for  $\Omega_0 \cdot J_0 \geq 0$ .

As a reference, in Fig.5, bottom frame, we plot the normalized value of the peaks of the total current  $J = |\mathbf{J}|$  at t = 350 as a function of z:  $max_{(x,y)}(J(x, y, z)) / max_x(J_0(x, z))$ . The maximal current increases at all latitudes due to the lateral compression of the original current sheet imposed by the KH velocity field. At the same time the current amplification is more important in the northern hemisphere as compared to the southern one because of differential advection.

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#### **4 Magnetic field line dynamics**

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#### 4.1 Overview of the dynamics

Most field lines maintain their connections during the whole dynamics even if strongly 353 bent and stretched by the KH vortical motion. In particular field lines on the left (right) of 354 the magnetopause iso-surface  $\varsigma = 0.6$  at t = 0 remain on the same side. On the other hand 355 the connections of some field lines, such as the yellow ones drawn in Fig. 6, are affected by 356 magnetic reconnection occurring various places at the magnetopause. Now, these field lines 357 connect two initially well separated magnetic domains, left and right of the magnetopause. 358 This is shown in Fig. 6, where such magnetic field lines cross the  $\varsigma = 0.6$  iso-surface at 359 several latitudes, from the magnetosheath (blue) to the magnetosphere (light blue), thereby 360 connecting both sides of the magnetopause. 361

The dynamics investigated here is more complex than that discussed in Faganello et al. 362 [2012a,b, 2014]; Borgogno et al. [2015]. It includes at the same time a pre-existing magnetic 363 shear between the magnetosheath and the magnetospheric fields and high-latitude stabiliza-364 tion of the KH instability, so that reconnection can occur both as Type I or mid-latitude re-365 connection. The former process is driven by the pinching of the pre-existing current sheet 366 caused by the compression in between KH vortices. Therefore it is expected to locally occur 367 where the instability grows the most [Chen et al., 1997; Knoll and Chacón, 2002; Nakamura 368 et al., 2006]. The latter is instead related to the field line differential advection and thus may 369 be triggered at current sheets created (or modified) by this advection, far away from the main 370 location of the KH vortices [Faganello et al., 2012a,b, 2014; Borgogno et al., 2015]. 371

We have shown in Fig.5, bottom frame, that in the presence of a sheared magnetic field 372 with  $\tan \varphi > 0$  the combined action of differential advection and lateral compression in-373 creases the electric current at all latitudes but in particular in the northern hemisphere, i.e. 374 in the hemisphere opposite to that where the vortices are most intense. On this basis we may 375 expect that Type I reconnection would preferentially occur around the equatorial region while 376 mid-latitude reconnection would be favoured in the northern hemisphere. In order to under-377 stand the development of such a complex dynamics we need to determine a quantity that can 378 act as a proxy for where reconnection occurs. 379

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#### 4.2 Finding reconnection: a 3D diagnostic

Determining reconnection sites in a full 3D, time-dependent geometry is far from 381 straightforward. When a pre-existing current sheet is present, the current density  $|\mathbf{J}|$  and the 382 magnetic shear already have quite "large" values, so they are not very useful when seeking 383 for reconnecting regions. The passive tracer  $\varsigma$  defined above (Eq. (12)) is, instead, a conve-384 nient proxy for defining "reconnected" field lines since only along these lines a variation of 385  $\varsigma$  can occur, i,e,  $\mathbf{B} \cdot \nabla \varsigma \neq 0$ . However, such a tracer cannot identify the precise location of 386 ongoing reconnection. 387

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Hence, in order to find reconnection active regions we define the following quantity:

$$\varkappa = (\partial_t + \mathbf{u} \cdot \nabla)(S_e - S_i) = (\mathbf{J} \cdot \nabla S_e)/n, \tag{16}$$

where Eqs. (1), (5) and (6) have been used. The idea behind this relies on the fact that in our 396 plasma model the entropy of each species is passively advected by its respective fluid veloc-397 ity. A difference between the electron and ion entropy advection thus indicate regions where 398 ions and electrons decouple which, in a Hall reconnection regime, include the reconnection 399 regions. We thus expect that magnetic field lines passing through regions where the value of 400 |z| peaks are those undergoing reconnection. These may be either magnetic field that have 401 not yet reconnected but that are advected by in-flows toward the center of the decoupling re-402 gion, or magnetic field lines that have just reconnected and are moving away following the 403 out-flows. Indeed, we observe in simulations that, as reconnection starts to act, the recon-404 nected field lines highlighted using |x| are those with the the largest jump of  $\varsigma$ , with respect 405 to that of several hundreds of randomly generated lines. Furthermore the value of the jump 406 of these highlighted lines increases with time, i.e. as reconnection proceeds. 407

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#### 4.3 Latitudinal distribution of the reconnection processes

In Fig.6 regions with large values of  $|\varkappa|$  are shown as red surfaces for simulation "B" 409 at t = 460. These active regions are all located in the upper part of the latitude band af-410 fected by the vortex structures, i.e. northwards with respect to the location where vortices 411 are most intense. With respect to the vortex axis, active regions appear as large sheets in cor-412 respondence to the hyperbolic points of the KH velocity field ("a." arrow) or as small scale 413 filamentary structures aligned with the local magnetic field direction at the northernmost 414 rippled boundary of the vortices ("b." arrow). We recall here that the hyperbolic points are 415

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located in between vortices. These sites are also called, in particular in observational papers,
 the "trailing edges" of KH vortices

When thought of in the frame of past works on the topic, these reconnection regions at 418 the hyperbolic point may be associated with either Type I or mid-latitude reconnection, since 419 both can occur there even if at different latitudes. However the usual distinction between both 420 types of reconnection loses its meaning when reconnection occurs over a large range of lati-421 tudes as observed here. We also note that the reconnecting regions appear as rather continu-422 ous patches from the latitude where vortices are most intense to the northernmost end of the 423 region affected by the KH instability. The only distinction concerns the mechanism by which 424 reconnection is driven, i.e. how the current is enhanced. At the location where the vortices 425 are most intense the magnetic shear grows mainly due to lateral compression, while in the 426 northern regions it increases mainly because of the magnetic field bending due to differential 427 advection. 428

For determining which mechanism is at work at different latitudes, we look at the temporal evolution of the reconnected component of the magnetic field and compare it to the evolution of the velocity field generated by the KHI. The reconnected component is defined as  $B_{rec} = \nabla \varsigma / |\nabla \varsigma| \cdot \mathbf{B}$ , the component normal to the  $\varsigma$  isosurfaces. This quantity generalizes the *x*-component of the magnetic field created by the linear evolution of Tearing instability in a 2D configuration with an equilibrium field given by  $B_{0,y} = B_0 \tanh(x/l)$ , described by eigenfunctions of the form  $B_{x,k}(x, y, t) = \tilde{B}_{x,k}(x)e^{iky}e^{\gamma_k t}$  [Faganello et al., 2012a].

In Fig.7 we show  $|u_x|$  (left) and  $|B_{rec}|$  (right) as a function of z and t for run "B". Both 440 quantities have been averaged over x and y.  $|u_x|$  gives a precise view on how and where the 441 KHI grows, in particular it develops a peak at z = -70, in the southern hemisphere as already 442 stressed in the previous section.  $|B_{rec}|$  has the same peak at z = -70 but also a long "summit 443 ridge" going from the main peak to a secondary one at z = 48. The main peak corresponds 444 to Type I VIR, indeed it is at the same location of the maximum of  $u_x$  that compresses the 445 original sheet. The secondary peak is related to a mid-latitude reconnection mechanism: in-446 dependently from its actual latitude, it develops far from the location where the vortices are 447 intense, at the latitude where the current is enhanced by differential advection only. 448

Type I reconnection is characterized by the fact the KH growth rate dictates the growth rate of reconnection [*Chen et al.*, 1997; *Knoll and Chacón*, 2002; *Nakamura et al.*, 2006], up to the early nonlinear phase. This is shown in Fig.8 where the amplitudes of the m = 2 mode

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(the KH FGM) of  $u_x$  (blue continuous lines) and  $B_{rec}$  (blue dot-dashed lines) are drawn as a function of time for z = -70. The reconnected component follows that of the velocity up to t = 400, with a growth rate comparable with the KH one  $\simeq 0.03$ . On the contrary midlatitude reconnection at z = 48 starts at a later time in the nonlinear phase and proceeds at a rate that is really different from that of  $u_x$  there, as shown by red lines.

Regarding the elongated reconnection regions, they are related to a small-scale rippling 457 of the magnetopause, with a wavevector nearly perpendicular to the local magnetic field. 458 This rippling appears at the northern edge of the region affected by the vortices and we con-459 jecture that it is related to a secondary instability that develops during vortex pairing, namely 460 the secondary KH instability [Cowee et al., 2009; Matsumoto and Seki, 2010; Tenerani et al., 461 2011] or Type II magnetic reconnection, i.e. reconnection related to the folding of the flow-462 aligned component of the magnetic field that occurs during the pairing [Faganello et al., 463 2008b, 2009]. In the former case it would be the velocity perturbations caused by the local 464 ideal instability to cause reconnection [Tenerani et al., 2011]. In the latter it would be re-465 connection itself to cause the plasma motion and thus the rippling. The detailed analysis of 466 secondary instabilities and induced reconnection is beyond the scope of this paper and will 467 be tackled in a future work. Nevertheless contrary to what is observed in 3D simulations ne-468 glecting high-latitude stabilization [Nakamura et al., 2013; Nakamura and Daughton, 2014], 469 in our simulations secondary instabilities occurs far away from the region where the primary 470 KH vortices are more intense. 471

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#### 4.4 Double reconnection processes

We define double-reconnected field lines as those lines that undergo reconnection 473 twice at different latitudes. About half of these lines connect the magnetosheath in the equa-474 torial region to the magnetospheric plasma at high latitudes (and viceversa). They are par-475 ticularly important, as compared to once-reconnected lines that simply "open" the magne-476 topause (allowing for the development of an open LLBL) because they can effectively trap 477 solar wind plasma onto closed field lines of the magnetosphere. Indeed, the flux tubes as-478 sociated to these lines can be considered as new magnetospheric flux tubes with their low-479 latitude portion populated by solar wind particles. Also, the creation of double-reconnected 480 flux tubes can explain the increase of the specific entropy of the cold ion population mea-481 sured just inside the magnetopause [Johnson and Wing, 2009]. Indeed, a statistical survey of 482 the low-latitude magnetosphere during northward periods shows that the cold dense popula-483

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tion of the magnetosheath leaks through the magnetopause increasing its specific entropy by
a factor 5 - 20.

In the absence of a pre-existing shear between the IMF and the magnetospheric field 486 double reconnection involves two locations along the same field line in the two opposite 487 hemispheres, acting in the northern as well as in the southern hemisphere in a nearly sym-488 metric way. Adding a magnetic shear to the system not only breaks the symmetry but changes 489 where and how reconnection develops. Recent MMS data show that reconnection occurs in 490 the region where the vortices are observed and also far away from the vortex location, pos-491 sibly at mid-latitude [Vernisse et al., 2016]. Our simulations confirm this scenario, showing 492 that for a positive magnetic shear angle  $(\tan \varphi > 0)$  reconnection occurs at the same time 493 where the vortices are most intense and in regions that are northern that this latitude (the op-494 posite is true for a negative magnetic shear angle,  $\tan \varphi < 0$ ). In addition our simulations 495 show that double-reconnected lines are generated during the late non-linear phase of the vor-496 tex dynamics for both tan  $\varphi = 0.3$  and tan  $\varphi = 1.0$ . An example of these lines is shown in 497 Fig.9 where lines are connected to the dark magnetosphere at high latitudes while crossing 498 the light blue magnetosheath plasma in the central part of the box. 499

#### 504 **5 Conclusions**

We have investigated the development of the Kelvin-Helmholtz instability and the in-505 duced reconnection processes in a geometry that models the configuration of the flanks of the 506 Earth's magnetosphere during periods of northward IMF by means of high-resolution Two-507 fluid simulations. Our initial configuration takes into account both the effect of high-latitude 508 stabilization and of a pre-existing magnetic shear between the magnetospheric and the mag-509 netosheath fields. The most remarkable features of the plasma dynamics observed in this 510 configuration are the latitude location where the KH instability grows more vigorously, the 511 place where induced magnetic reconnection occurs and the mechanism underlying induced 512 reconnection. 513

<sup>514</sup> Concerning the first point, as soon as the IMF has a component along the flow (de-<sup>515</sup> scribed by a shear angle  $\varphi$  in our simulations) the reflection symmetry about the equatorial <sup>516</sup> plane is broken even if the density, temperature and velocity field are symmetric (the north-<sup>517</sup> ward component of the magnetic field is symmetric too). In particular, we have shown that <sup>518</sup> KH vortices develop asymmetrically with respect to the equatorial plane depending on the

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<sup>519</sup> sign of the pseudoscalar  $\Omega_0 \cdot \mathbf{J}_0$ , where  $\mathbf{J}_0$  is the equilibrium current associated to the rotation <sup>520</sup> of the equilibrium magnetic field across the magnetopause and  $\Omega_0$  is the equilibrium vortic-<sup>521</sup> ity associated to the velocity shear. When  $\Omega_0 \cdot \mathbf{J}_0 > 0$ , KH vortices fully develop mainly in <sup>522</sup> the southern hemisphere, whereas the contrary is true for  $\Omega_0 \cdot \mathbf{J}_0 < 0$ .

From a physical point of view the shift of the vortices towards one hemisphere can be explained by looking at the dynamics of magnetic field lines at the beginning of the nonlinear phase. In fact, even if the linear KH growth rate is symmetric, the dynamics of field lines is not. Indeed, the magnetic field lines are frozen in the plasma fluid motion and are advected differently at high latitudes, where the magnetospheric/solar wind velocity stays unperturbed, and at low latitude where the instability develops. This differential advection causes the averaged magnetic field shear to increase in one hemisphere and to be reduced in the other one. Since the magnetic shear tends to inhibit the KH growth, vortices develop asymmetrically.

Since both  $\Omega_0$  and  $J_0$  change sign when passing from the magnetospheric dusk flank to the dawn flank, the hemisphere where the vortices are more intense is the same at both flanks, e.g. the southern one if the flow-aligned component of the IMF is positive. This fact can be directly inferred from the symmetry properties of the system: the dawn flank configuration can be obtained from the dusk one by reflecting the system with respect to the magnetopause and applying charge-conjugation. Since MHD equations are invariant under "reflection + charge-conjugation", the large-scale KH dynamics is specular.

In the past, Farrugia et al. [1998] and Gratton et al. [2003] considered the impact of 538 the clock angle of the IMF on the KH instability, i.e. the impact of a westward component 539 of the magnetic field, perpendicular to both the northward and the flow directions. Neglect-540 ing the flow-aligned component of the IMF, they showed that for a positive clock angle the 541 location of the maximum linear growth rate of the KH instability is located in the northern 542 hemisphere at the dusk side. The opposite is true at the dawn flank so that the most unsta-543 ble hemispheres are different at the dawn/dusk sides. This behaviour has been obtained by 544 looking at the configuration of the magnetic field close to the global magnetopause, taking 545 into account the dipolar configuration of the magnetospheric field and the draping of the so-546 lar wind magnetic field around the magnetopause as described by a global MHD code. From 547 a symmetry point of view this fact is not surprising since as soon as a westward component 548 of the magnetic field is considered the global system is no more invariant under "reflection 549 + charge-conjugation" so that the dawn and dusk large-scale dynamics are not specular (here 550

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the reflection of the global system is about the plane defined by solar wind direction and the northward direction, passing through the Earth).

In our configuration the clock angle is not included so that the nonlinear KH activity at the flanks is specular. On the contrary when considering the clock angle but neglecting the shear angle [*Farrugia et al.*, 1998; *Gratton et al.*, 2003] the linear dynamics is anti-specular. Taking into account both the shear angle and the clock angle effect would help in clarifying satellite data analysis, in particular when KH activities measured at both flanks (at different latitudes) are compared [*Hasegawa et al.*, 2006; *Nishino et al.*, 2011; *Taylor et al.*, 2012].

The magnetic shear angle has a similar but opposite impact on the location where re-559 connection occurs, with respect to the location where the KH vortices eventually settle, since 560 reconnection develops faster in regions where the magnetic shear is larger. The local mag-561 netic shear is enhanced in two different ways during the nonlinear dynamics. The first one is 562 the pinching of the pre-existing current sheet that occurs at the hyperbolic point (in between 563 successive vortices) of the KH velocity field, as in Type I reconnection. The second one is 564 the modification of the pre-existing current sheet far away from the location where vortices 565 are intense due to differential advection and field line bending. The local magnetic shear be-566 comes larger in the hemisphere opposite to the one where KH vortices are more developed, 567 i.e. in the northern (southern) hemisphere for a positive (negative)  $\Omega_0 \cdot J_0$ . Both mechanisms 568 are at work in our simulations, leading to the development of reconnection in a wide latitude 569 range: from the location where vortices are most intense to the upper (lower) edge of the re-570 gion affected by KH perturbations. 571

Recent MMS observations on 8 September 2015 suggest that Type I reconnection pro-572 ceeds nearby vortices [Eriksson et al., 2016] and that, at the same time, remote reconnection 573 occurs probably at mid latitudes [Vernisse et al., 2016]. The simulations discussed here re-574 produce this dynamics and and further suggest that remote reconnection should be favoured 575 in a given hemisphere depending on the initial magnetic shear (i.e., the prevailing IMF orien-576 tation). In particular when the flow-aligned component of the IMF is negative, as during this 577 peculiar MMS observations, the favoured hemisphere is the southern one. This is compatible 578 with the fact that the number of remote reconnection events observed on this day by MMS is 579 bigger in the southern than in the northern hemisphere [Vernisse et al., 2016]. 580

<sup>581</sup> Our simulations also show that reconnection, going on at different latitudes, is able <sup>582</sup> to produce double-reconnected magnetic field lines connected to the Earth and thus to trap

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583	dense magnetosheath plasma inside the magnetopause even when a significant magnetic
584	shear is present in the initial configuration. These results indicate that this double reconnec-
585	tion process associated with KH vortices is a viable mechanism to explain the formation of
586	the flank LLBL even in the presence of significant magnetic shear. Future work shall focus
587	on determining the efficiency of this mechanism as a function of the initial magnetic shear.
588	
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**Figure 1.** Schematic representation of the magnetic and velocity fields in the equilibrium configuration.

 $\varphi$  represents the angle between the IMF and the northward direction  $\hat{\mathbf{z}}$ .  $\vartheta$  defines the angle between a given

wavevector **k** lying in the (*y*, *z*)-plane and the flow direction  $\hat{\mathbf{y}}$ .



Figure 2. Visual rendering of the instability onset and development for  $\tan \varphi = 1.0$  ("B" simulation) at t = 460. The shaded isosurface ( $\varsigma = 0.6$ ) corresponds to the magnetopause while dark/light blue colours correspond to the magnetospheric/solar wind plasmas. The white isocontours correspond to the passive tracer values  $\varsigma = 0.3, 0.6, 0.9$ . Note that for easing the visualization the box has been doubled along the y-direction.



Figure 3. Shaded iso-contours of the *x*-averaged Fourier amplitude of  $u_x$ , normalised on the characteristic velocity  $u_{\star}$ , taken at t = 400 for tan  $\vartheta = 0.3$  and tan  $\vartheta = 1.0$ , left and right frames, respectively. The continuous lines represent the most unstable modes given by the (n,m) couples as predicted from the analytical step-like configuration. The dashed line by  $\vartheta_{shear} = -\arctan[(\tan \varphi)/2]$ . For each discrete *m*-value, a cross indicates the location of maximal amplitude as obtained in simulations. Clearly crosses are almost aligned along the continuous line.



**Figure 4.** A sketch of the differential magnetic field line advection mechanism for tan  $\varphi > 0$ . The figure 292 shows a magnetospheric/IMF line, light blue and dark blue colours respectively, at three different times. The 293 unperturbed field lines, denoted by  $t_1$ , first bend close to the equators, resulting into magnetic field lines at 294 time  $t_2$ , due to the different advection at high/low latitudes, i.e. field lines move unperturbed in opposite di-295 rections at high latitudes while they are slowed down in the equatorial plane. Indeed, as the field lines are 296 frozen into the fluid motion, they are slowed down in the equatorial plane because they are embedded in the 297 vortex structures whose phase velocity is nearly zero. The magnetic shear is thus enhanced in the northern 298 hemisphere and reduced in the southern one causing a southward drift of the instability. As a consequence the 299 region where magnetic field lines are slowed down gradually shifts southward, as shown for  $t = t_3$ , as well as 300 the region with smaller magnetic shear, favouring the KH development. 301



Figure 5. Top frame:  $max_x(\tilde{J}_{m=0}(x, z)) / max_x(J_0(x, z))$  as a function of z at t = 250, 300, 350. Bottom frame:  $max_{(x,y)}(J(x, y, z)) / max_x(J_0(x, z))$  at t = 250 (dash-dotted), t = 300 (dashed), t = 350 (continuous).



Figure 6. Shaded isosurface ( $\varsigma = 0.6$ ) corresponding to the magnetopause and dark/light blue colours corresponding to the magnetospheric/magnetosheath plasmas for tan  $\varphi = 1.0$  at t = 460. The white isocontours correspond to the passive tracer values  $\varsigma = 0.3, 0.6, 0.9$ . The regions where reconnection takes place are enclosed in the  $|\varkappa| > 0.03$  volumes, highlighted in red. The black arrows indicate planar (label "a.") and elongated (label "b.") reconnection sites. Some magnetic field lines representative of those crossing the active reconnecting sites have also been drawn - in yellow if reconnected, in green if not. Note that for easing the visualization the box has been doubled along the y-direction.



Figure 7. Left:  $|u_x|$  averaged over x and y as a function of z and t. Right:  $|B_{rec}|$  averaged over x and y as

430 a function of z and t.



Figure 8. Time evolution of the magnitude of the m = 2 mode of  $u_x$  at z = -70 (blue continuous line) and z = 48 (red continuous line) and of  $B_{rec}$  at z = -70 (blue dot-dashed line) and z = 48 (red dot-dashed line).



Figure 9. Shaded isosurface ( $\varsigma = 0.6$ ) corresponding to the magnetopause and dark/light blue colours corresponding to the magnetospheric/magnetosheath plasmas for tan  $\varphi = 1.0$  at t = 460. The white isocontours correspond to the passive tracer values  $\varsigma = 0.3, 0.6, 0.9$ . Magnetic field lines are colored using the local value of  $\varsigma$ . Note that for easing the visualization the box has been doubled along the y-direction.