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Satellite data-based 3D simulation of Kelvin-Helmholtz instability and induced magnetic reconnection at the Earth's magnetopause

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Key Points:

4

9	- We present a 3D two-fluid simulation using plasma parameters as measured by
10	MMS on September 8th 2015
11	• We observe that vortex induced and mid-latitude magnetic reconnection coexist
12	• We estimate the effective diffusion coefficient associated with reconnection, ob-
13	taining $D_{eff} \simeq 10^{10} m^2/s$, large enough to explain the observed mixing

14 Abstract

We present a 3D two-fluid simulation using plasma parameters as measured by MMS on 15 September 8th 2015 concerning the nonlinear development of the Kelvin-Helmholtz in-16 stability at the Earth's magnetopause. We observe an extremely rich nonlinear dynam-17 ics including the development of a complex magnetic topology, vortex merging and sec-18 ondary KH instability driven by large-scale vortices distributed asymmetrically in lat-19 itude. Vortex induced and mid-latitude magnetic reconnection coexist and produce an 20 asymmetric distribution of magnetic reconnection events. These results are in good agree-21 ment with MMS observations on the same day, in particular for the presence of both equa-22 torial and off-equator reconnection. Regarding the latter only we note a predominance 23 of reconnection in the southern hemisphere during the early nonlinear phase. The es-24 timated effective diffusion coefficient associated with the dynamics is found to be large 25 enough to account for the observed mass transport at the Earth's magnetospheric flanks. 26

27 1 Introduction

Several decades of studies definitely proved the key role played by the Kelvin-Helmholtz 28 instability (KHI) in regulating plasma transport from the solar wind (SW) into plane-29 tary magnetospheres. In particular, satellite data collected around the Earth's magne-30 topause revealed the presence of rolled-up KH vortices (Hasegawa et al., 2004) under a 31 variety of SW magnetic field orientations (Hasegawa et al., 2006; Hwang et al., 2011; Far-32 rugia et al., 2014; Kavosi & Raeder, 2015) and the direct proof of magnetic reconnec-33 tion events forced by the vortices themselves (Hasegawa et al., 2009; Eriksson et al., 2016). 34 This proof is of paramount importance since KH vortices alone cannot explain the ob-35 served transport. Vortices develop as large-scale, nearly magnetohydrodynamic (MHD) 36 structures that strongly perturb and fold the magnetopause but preserve the magnetic 37 topology. Thus, they cannot induce an effective transport (Foullon et al., 2008; Nykyri 38 & Otto, 2001). In contrast, new open field lines emerging from reconnection events al-39 low particles to stream from the SW into the magnetosphere leading to direct plasma 40 entry (Nakamura & Daughton, 2014; Daughton et al., 2014). This kind of dynamics is 41 of great interest also for planetary magnetospheres (Johnson et al., 2014) and magne-42 tized astrophysical objects characterized by the presence of strong velocity gradients (Lovelace 43 et al., 2010; Li & Narayan, 2004). 44

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Here we focus our analysis on northward Interplanetary Magnetic Field (IMF) pe-45 riods at Earth when the magnetic field advected by the SW is mainly parallel to the mag-46 netospheric one at low-latitude, but including a rotation in the transition from the SW 47 to the magnetosphere. In this region KH vortices can effectively grow with wavevectors 48 nearly perpendicular to the average magnetic field minimizing the effect of magnetic ten-49 sion, but still fairly aligned with the flowing SW maximizing the velocity shear driver 50 (Faganello & Califano, 2017; Southwood, 1968; Walker, 1981; Miura & Pritchett, 1982). 51 If an initial magnetic rotation is taken into consideration, the associated current sheet 52 is pinched in between vortices and Type I Vortex Induced Reconnection (VIR) is forced 53 on the ideal KH time-scale, faster than the usual reconnection one (Chen & Morrison, 54 1990; Knoll & Chacón, 2002). VIR creates "open" field lines crossing the magnetopause 55 eventually producing the development of a mixing layer (Nakamura et al., 2013). At mag-56 netopause flanks, the KHI is gradually stabilized at higher latitudes (Farrugia et al., 1998; 57 Gratton et al., 2003; Contin, 2003). As a result magnetic field lines are advected differ-58 ently at low latitude, once engulfed in vortices, and at high latitudes where the flow is 59 more and more unperturbed. In such a way, even if IMF and magnetospheric field lines 60 are aligned, so that no magnetic rotation is present, mid-latitude current sheets are cre-61 ated where reconnection finally occurs (Faganello, Califano, Pegoraro, & Andreussi, 2012; 62 Borgogno et al., 2015). Proceeding at the same time in both hemispheres, mid-latitude 63 reconnection (MLR) is able to create twice-reconnected, "newly closed" field lines con-64 nected to the Earth at both poles while embedded within SW plasma at low-latitude. 65 Twice-reconnected field lines allow for a direct and effective injection of SW plasma into 66 the magnetosphere (Faganello, Califano, Pegoraro, & Andreussi, 2012; Johnson & Wing, 67 2009). Measurements of *remote* reconnection signatures using electron particle fluxes have 68 been reported by Cluster (Bavassano Cattaneo et al., 2010), Themis (Faganello et al., 69 2014) and MMS (Vernisse et al., 2016). In these works the location of reconnection sites 70 is inferred by looking at the angle of detected suprathermal particles with respect to lo-71 cal magnetic field: parallel particle fluxes are related to events occurring in the south-72 ern hemisphere, while antiparallel fluxes come from events in the northern one. Inter-73 estingly, MMS observations on September 8th 2015 indicate that VIR proceeding at equa-74 torial latitude and MLR coexist (Eriksson et al., 2016; Vernisse et al., 2016). MMS was 75 located close to the GSE equatorial plane where vortices and *in-situ* VIR outflows were 76 detected. At the same time satellites observed parallel and antiparallel particle fluxes 77

as signatures of *remote* reconnection, with more events with parallel fluxes. This fact sug-78 gests that the latitudinal distribution of *remote* reconnection events was asymmetric, with 79 more events located in the southern hemisphere rather than in the northern one. This 80 dynamics have been confirmed by numerical simulations taking into account high-latitude 81 stabilization as well as the initial magnetic rotation (Fadanelli et al., 2018), but not the 82 actual magnetic/plasma parameters of the observed MMS event. The magnetic rotation 83 breaks the reflection symmetry with respect to the equatorial plane so that the system 84 evolves differently in the two hemispheres. As a consequence, MLR and the production 85 of twice-reconnected lines could be affected (Fadanelli et al., 2018; Ma et al., 2017). At 86 the same time local kinetic simulations of this MMS event have been performed focus-87 ing on VIR only (Nakamura, Hasegawa, et al., 2017; Nakamura, Eriksson, et al., 2017), 88 showing that VIR can become turbulent producing a layer where different particle pop-89 ulations are effectively mixed-up, with a local entry rate comparable with that required 90 for the observed mass transfer during northward IMF periods (Sonnerup, 1980). How-91 ever, for such simulations, the numerical box has a limited size in latitude, thus they can-92 not reproduce the *remote* dynamics of MLR. 93

Here we analyze a 3D two-fluid simulation using the parameters measured during 94 the MMS event of September 8th 2015 and a large enough numerical box in order to in-95 clude high-latitude stabilization. We show, in agreement with MMS observations, that 96 VIR and MLR coexist and determine the complex magnetic field topology. To summa-97 rize: i) even if the symmetry of mid-latitude reconnection is broken by the presence of 98 the large scale magnetic field rotation, the production of twice-reconnected field lines is 99 still efficient, ii) the effective diffusion coefficient associated with such a complex topol-100 ogy can explain the observed transport in a wide latitude range, iii) the asymmetry of 101 reconnection events reproduces that observed during the MMS event on which the sim-102 ulation parameters are set, iv) the late nonlinear phase is extremely rich with vortex merg-103 ing and the development of secondary KH instability that boost the production of re-104 connected lines and the effective diffusivity. Our simulation is able to account for the main 105 features characterizing the dynamics as inferred from MMS data on September 8th 2015 106 (Eriksson et al., 2016; Vernisse et al., 2016) and predicts an even more complex evolu-107 tion of the magnetic topology when moving tailward as compared to the satellite posi-108 tion. 109

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¹¹⁰ 2 Plasma model and simulation setup

We consider a slab geometry with the x-axis perpendicular to the magnetopause, z as the latitude and the y-axis along the SW flow. The plasma evolution is described by a two-fluid set of equations:

$$\partial_t n + \nabla \cdot (n\mathbf{U}) = 0 \quad ; \quad n = n_i \simeq n_e$$
 (1)

$$\partial_t(n\mathbf{U}) + \nabla \cdot \left[n\mathbf{U}\mathbf{U} + (P_i + P_e + B^2/2)^{\overline{\mathbf{I}}} - \mathbf{B}\mathbf{B} \right] = 0$$
⁽²⁾

$$\partial_t (nS_j) + \nabla \cdot (nS_j \mathbf{u}_j) = 0 \quad ; \quad S_j = P_j n^{-5/3} \quad ; \quad j = i, e \tag{3}$$

where *n* is the plasma density, $\mathbf{u}_i \simeq \mathbf{U}$ the ion fluid velocity, $\mathbf{u}_e = \mathbf{U} - \mathbf{J}/n$ the electron fluid velocity, $\mathbf{J} = \nabla \times \mathbf{B}$ the current density and P_j , j = i, e, the pressures. All quantities are normalized using the ion mass and charge, the ion skin depth d_i and the z-component of the Alfvén velocity at the center of the simulation domain. The Faraday equation and a generalized Ohm's law,

$$\mathbf{E} = -\mathbf{u}_e \times \mathbf{B} - \frac{1}{n} \nabla P_e + \eta \mathbf{J},\tag{4}$$

complete the set. We use a small but finite resitivity $\eta = 10^{-3}$, corresponding to 119 a resistive diffusion time scale $\tau_R \simeq \eta^{-1} a^2 \simeq 10^4$, associated with the equilibrium scale 120 length a, which is far bigger than the simulation time. As a consequence the magnetic 121 field is frozen-in to the large-scale KH motion and we don't observe any appreciable mag-122 netic diffusion until reconnection starts in d_i -scale current sheets. Here reconnection is 123 expected to develop on a time scale nearly independent of the η value as for Hall-dominated 124 reconnection (Birn et al., 2001). Even if a kinetic model would better reproduce the finer 125 structures of magnetic reconnection, our description is nevertheless able to capture the 126 correct reconnection time-scale in the complex 3D evolution of KHI and to describe the 127 evolution of the global magnetic topology (Faganello, Califano, Pegoraro, & Andreussi, 128 2012). We model the initial large-scale configuration by using a 2D Grad-Shafranov equi-129 librium that includes the strong gradients across the magnetopause and reproduces the 130 high-latitude stabilization along z (Faganello, Califano, Pegoraro, Andreussi, & Benkadda, 131 2012). All equilibrium quantities are obtained by a flux function 132

$$\psi(x, z, t = 0) = \frac{2}{3}x + \frac{1}{3}\frac{L_z}{2\pi}\sinh\frac{2\pi x}{Lz}\cos\frac{2\pi z}{L_z}$$
(5)

133	giving $\mathbf{B}_{eq} = \nabla \psi \times \hat{\mathbf{y}} + (B_{flow}/2) \left[1 + \tanh(\psi/a)\right] \hat{\mathbf{y}}, \ n_{eq} = 1 + (\Delta n/2) \tanh(\psi/a),$
134	$\mathbf{U}_{eq} = (\Delta U/2) \tanh(\psi/a) \mathbf{\hat{y}}, P_{i,eq} + P_{e,eq} + B_{eq,y}^2/2 = (P_{i,eq} + P_{e,eq} + B_{eq,y}^2/2) _{\psi=0}$ with
135	$P_{i,eq} = 4 P_{e,eq}$. Here B_{flow} is the flow-aligned component of the IMF that, adding to
136	the northward component of the magnetic field, reproduces its rotation. We take equi-
137	librium quantities compatible with the MMS event, as given by the values reported in
138	the outer magnetosphere and in the adjacent magnetosheath in the auxiliary material
139	of Eriksson et al. (2016). In particular n varies from $5.7 cm^{-3}$ to $20.1 cm^{-3}$, with an av-
140	eraged value of $\sim 13 cm^{-3}$. Using this value when normalizing, we have $n = 1$ at the
141	magnetopause and $\Delta n = 1$. The GSE z-component of the magnetic field is nearly con-
142	stant at $\sim 67nT$ while the flow aligned component in the sheath is $\sim -24nT$. The ve-
143	locity jump is ~ $350 km/s$. As a consequence normalized quantities read $B_{z,eq} _{\psi=0}$ =
144	1, $B_{flow} = -0.3$ and $\Delta U = 0.9$. The thermal temperature varies from $T_{th} = T_i +$
145	$T_e=2638 eV+124 eV\sim 2800 eV$ to $T_{th}=T_i+T_e=189 eV+36 eV\sim 200 eV;$ thus the
146	averaged thermal temperature is ~ 1500eV and $(P_{i,eq} + P_{e,eq}) _{\psi=0} = 0.9$. The pres-
147	sure equilibrium condition given above reproduces a temperature jump across the mag-
148	netopause of $\sim~2080 eV,$ slightly less but consistent with the MMS data. We set $a~=$
149	3 so that the fastest growing mode (FGM) wavelength $\lambda_{FGM} \simeq 4\pi a$ is big as compared
150	to d_i and KH vortices develop at MHD scales. The box size is given by $L_x = 90 \simeq 2.4 \lambda_{FGM}$,
151	$L_y = 24\pi = 2\lambda_{FGM}, L_z = 96\pi = 8\lambda_{FGM}$. The number of grid points is $n_x = 600$,
152	$n_y = n_z = 512$. All details on the numerical code, including transparent boundary
153	conditions, can be found in Fadanelli et al. (2018) and references therein.

¹⁵⁴ **3** Data analysis

In Fig.1, panel a, we show a 3D rendering of the KH vortices at t = 525. Vortices 155 develop around the equator while high-latitude regions are stable. The vortex axis, as 156 shown by the folded shaded surface of the magnetopause, is tilted with respect to $\hat{\mathbf{z}}$ since 157 the FGM wavevector is nearly perpendicular to the average \mathbf{B}_{eq} in the central region. 158 This tilting is also underlined by the three central planes drawn perpendicularly to the 159 vortex axis. As expected for $B_{flow} < 0$ (Fadanelli et al., 2018), vortices are more in-160 tense above the equatorial plane since the differential advection of field lines enhances 161 the magnetic rotation in the southern hemisphere and lower it in the northern one. In-162

deed, as shown in panel b, $max_{(x,y)}(|J_{\parallel}|)$ (the maximum is searched in the entire xy-plane) 163 as a function of z becomes larger and larger in the southern hemisphere (here $J_{\parallel} = \mathbf{J}$. 164 $\mathbf{B}/|\mathbf{B}|$). Since the presence of a magnetic rotation tends to stabilize the KHI (see panel 165 b), the vortices are favoured above z = 0 (panel c) where $max_{(x,y)}(u_{ix})$ is larger in the 166 northern hemisphere. Panels d, e, f show density isocountours at different stages of the 167 vortex evolution above the equator (at z = 68, close to the latitude where the vortices 168 are more intense): at t = 500 when vortices are fully rolled-up, at t = 600 when they 169 start to merge (Miura, 1997), at t = 725 when a single large-scale vortex has formed 170 while small-scale secondary KHI (Matsumoto & Hoshino, 2004; Smyth, 2003) develops 171 at the low-density boundary of the vortex where strong velocity gradients exists. At z =172 -30 (where the current peaks) KH nonlinear evolution proceeds in similar way (slightly 173 less intense rolled-up vortices that finally merge), but no sign of secondary KHI appears, 174 probably due to the enhanced magnetic shear. The evolution of $|J_{\parallel}|$ suggests that VIR 175 should occur close to the equatorial plane at $t \sim 500$ where a single broad current peak 176 is generated by the vortex pinching of the initial current sheet, see panel b, continuous 177 line. Later on, at t = 600 a secondary current peak is visible at $z \sim 100$ so that MLR 178 is expected to occur in the northern hemisphere (dashed line), while the main broad peak, 179 although shifted southward by differential advection, would remain linked to VIR. Since 180 reconnection in a 3D geometry is not trivial to be identified, we follow the ideal MHD 181 evolution of the initial magnetic surfaces by integrating in time $\partial_t \psi + \mathbf{U} \cdot \nabla \psi = 0$. At 182 t=0 $|\psi|$ measures the distance from the (perturbed) magnetopause, with $\psi \simeq x$ around 183 z = 0.184

To look at reconnected field lines, we trace at given times a set of 22500 magnetic 185 field lines whose feet are uniformly distributed in the (x, y) region $[-15, 15] \times [0, L_y]$ at 186 $z = -L_z/2$. We define a line as "reconnected" when ψ has a jump along the line of at 187 least $\pm a/2$ across the magnetopause. "Once-reconnected" lines have only one jump, "twice-188 reconnected" lines have two jumps, and we call "2⁺-reconnected" lines with three or more 189 jumps. In order to provide a visual representation of the previous definitions, in Fig.2, 190 panel a, we plot the value of ψ along two chosen magnetic field lines. One is once-reconnected 191 and has a single ψ -jump around $z \lesssim 0$, while the other is twice-reconnected having a 192 second jump around $z \sim 100$. Note that around both latitudes, where the connection 193 changes occur, we observe clear ion and electron outflows pointing away from the site 194 where the parallel current is maximal and where reconnection is proceeding (see Fig. S1 195

and S2 of Supporting Information). Signatures of the Hall quadrupole are visible below 196 z = 0, even if quite distorted because of the "guide field" effect (Eastwood et al., 2010) 197 and of the density asymmetry across the current sheet (Pritchett, 2008). A kinetic de-198 scription would probably reduce the distortion associated with the density asymmetry 199 since particles streaming along reconnected field lines would rapidly smooth out density 200 variations (Sturner et al., 2018). At $z \sim 100$ the magnetic fluctuations due to the KH 201 vortex strengthen, suppressing possible quadrupolar signatures (see Fig. S3 and S4 of 202 Supporting Information). 203

For all field lines having a jump in ψ we record the latitude at which they cross the 204 magnetopause in order to obtain a latitudinal distribution of sites of connection changes 205 (Fig.2, panel b). At t = 525 this distribution is peaked just below z = 0 where VIR 206 has created once-reconnected field lines. At $t\,=\,600$ a second bump around $z\,\sim\,100$ 207 is present corresponding to lines having reconnected a second time in the northern cur-208 rent peak due to MLR. The main peak associated with VIR has moved southward, as 209 the main current peak did. These dynamics are confirmed by the temporal evolution of 210 the number of once- or twice-reconnected lines, see Fig.2, panel c. At the beginning only 211 once-reconnected lines are present and their number increases in time. After a while they 212 reconnect a second time at mid latitude (in correspondence of the northern current peak, 213 not shown) and the number of twice-reconnected lines increases too. The ratio between 214 once- and twice-reconnected lines slowly increases in time (panel d) until $t \sim 675$ sug-215 gesting that the dynamics favour an efficient conversion from once- to twice-reconnected 216 lines. After $t \sim 675$ this ratio reaches a plateau corresponding to nearly 60% of twice-217 reconnected lines. Even if not all once-reconnected lines reconnect a second time, the num-218 ber of lines doing this is far from being negligible. The production rate of twice-reconnected 219 line is smaller by a factor of three than in the case without an initial magnetic rotation 220 (Borgogno et al., 2015) but is of the same order of magnitude. The number of 2^+ -reconnected 221 lines stays negligible. 222

Reconnection leads to the development of a mixing layer across the magnetopause where field lines have different topologies, from the original one, to "open" connection and "newly closed" ones. Because the mixing between the different populations is dominated by parallel streaming along reconnected lines (Daughton et al., 2014; Nakamura et al., 2013), in our fluid approach we look at the average displacement of magnetic field lines with respect to their initial distance from the magnetopause. We thus evaluate <

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 $\Delta \psi^2 >$, where the average is on the set of 22500 field lines defined above, $\Delta \psi = max(\psi) - \omega^2$ 229 $min(\psi)$ along a line and where $\sqrt{\langle \Delta \psi^2 \rangle}$ would thus correspond to the average width 230 of the mixing layer. As shown in Fig.2, panel $e_{,} < \Delta \psi^2 >$ grows linearly in time from 231 $t \simeq 575$ to $t \simeq 675$, indicating a diffusive-type widening of the mixing layer, with an 232 effective magnetic and matter diffusion coefficient $D_{eff} \simeq 0.1 v_{A,z} d_i$. Taking a z-component 233 of the Alfvén velocity $v_{{\scriptscriptstyle A},z}$ \simeq 400 km/s and d_i \simeq 300 km (which corresponds to a KH 234 wavelength $\lambda_{KH} \simeq 12000 \, km$, as inferred in the MMS event) we obtain $D_{eff} \simeq 10^{10} \, m^2/s$, 235 even bigger than the diffusion coefficient needed to account for the observed plasma mix-236 ing in a simplified viscous model of the magnetopause (Sonnerup, 1980). 237

Since all new connection changes observed during a given time interval are due to 238 reconnection events, we can compare the spatial distribution of reconnection sites ob-239 tained in our simulation with the ones inferred during the MMS event (Vernisse et al., 240 2016). In order to reproduce a magnetopause crossing by a virtual satellite at equato-241 rial latitudes, we define three cases: 1) *in-situ* reconnection sites (with respect to the MMS 242 spacecraft position) when the magnetopause crossing is located around the equators $(-10 d_i <$ 243 $z < +10 d_i$; 2) remote sites in the northern hemisphere for a crossing at $z > +10 d_i$; 244 3) remote sites in the southern hemisphere for a crossing at $z < -10 d_i$. These defini-245 tions are related to the satellite position, not to the type of reconnection going on. The 246 results for different time intervals are listed in Tab.1. In agreement with the MMS event 247 (Vernisse et al., 2016) in the early nonlinear phase ($t \leq 600$) the most of the *remote* 248 reconnection sites are located in the southern rather than in the northern hemisphere. 249 Note that vortices are expected to be in their early nonlinear phase for this event, as in-250 ferred by Nakamura, Hasegawa, et al. (2017) by a careful comparison between their lo-251 cal simulation and the MMS observations. Moreover MMS satellites are close to the GSE 252 equatorial plane (Eriksson et al., 2016), where the growth rate of the KHI is supposed 253 to be close to its maximum (Vernisse et al., 2016). In our case, this plane correspond to 254 the z = 0 one. 255

In order to interpret the complex topology extrapolated from MMS data, in Fig.3 we draw the density iso-contours corresponding to a 2D chart of vortices in the equatorial plane during the early nonlinear phase, together with the intersection points of reconnected field lines. At t=550 black circles symbolize once-reconnected lines, generated by VIR. These lines intersect the selected plane close to the compressed current sheet between vortices. The number of these intersection points gradually increases in time

along the vortex arms. An "arm" is defined as the low (high) density plasma plume that 262 is gradually folded into a vortex, e.g. the blue (red) region in between $y\sim 20$ and $y\sim$ 263 40, at $x \sim 2$ ($x \sim -5$). Since these lines reconnect at $z \leq 0$, satellites at $z \simeq 0$ would 264 measure either in-situ reconnection signatures, for example reconnection outflows and 265 Hall magnetic field, or accelerated particles streaming parallel to **B** (coming from the 266 south). It is worth noticing that due to the relative motion of vortices during their merg-267 ing, the current sheet centered at $y \sim 20$ is more compressed and enhanced as compared 268 to the one in $y \sim 55$. At later times, t = 575, some field lines have also reconnected a 269 second time also in the northern hemisphere (purple points) and satellites encountering 270 these twice-reconnected field lines would also observe also antiparallel particle fluxes. Note 271 that black intersection points are located either close to the compressed current sheet 272 or along vortex arms while purple points are only located along vortex arms. This kind 273 of behaviour associated with *remote* mid-latitude reconnection, for which antiparallel fluxes 274 of accelerated particles from northern reconnection sites could be detected only along 275 the vortex arms, could help in discerning this type of reconnection mechanism from other 276 kinds of *remote* reconnection events, such as lobe reconnection (Gosling et al., 1991; Song 277 & Russell, 1992; Le et al., 1994), for which the intersection points would be equally dis-278 tributed between the compressed current sheet and the vortex arms. 279

In the late nonlinear phase, vortices first merge ($t \simeq 600$) and then the single large 280 vortex turns out to be unstable with respect to secondary KHI ($t \simeq 700$) that devel-281 ops at latitudes around $z \simeq 70$. During vortex merging the increase of reconnected lines 282 is slightly slowed down (Fig.2, panel c) while more events are recorded in the northern 283 hemisphere than in the southern one (see Tab.1). When, for $t \simeq 700$, secondary KHI 284 grows along the vortex SW arm around $z \simeq 70$, it forces reconnection to occur and boosts 285 the production of reconnected lines. As a consequence the latitude distribution of recon-286 nection sites changes from a two-bump structure (Fig.2, panel b, blue line) to a single 287 wider distribution (panel b, red line) with lots of magnetopause crossings from $z \simeq -70$ 288 to $z \simeq 130$. 289

290

4 Discussion and Summary

By performing a 3D two-fluid simulation using the parameters measured by MMS on September 8th 2015 and using a large numerical box including high-latitude stabilization, we have studied the development of *remote* northern MLR together with vortex-

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induced reconnection. Even if the North-South symmetry of the system is broken, the 294 production of twice-reconnected lines turns out to be fairly efficient with 60% of once-295 reconnected lines reconnecting a second time. An estimation of the diffusion coefficient 296 D_{eff} associated with reconnection turns out to be large enough to explain the observed 297 plasma mixing (Sonnerup, 1980) and compatible with the one inferred by Nakamura, Eriks-298 son, et al. (2017); Nakamura, Hasegawa, et al. (2017) where, however, the numerical box 200 is too small to account for the *remote* dynamics. Two main regimes have been identi-300 fied thanks to the analysis of connection changes. In the early nonlinear phase VIR and 301 northern MLR coexist and generate a latitudinal distribution of connection changes with 302 two different bumps at different latitudes. Following a virtual satellite around the equa-303 torial plane we observe, as found by MMS, more "remote" events in the southern hemi-304 sphere than in the northern. However, while Vernisse et al. (2016) identify southern "re-305 mote" events as MLR our simulation suggests that they could be related to VIR, which 306 is found to develop in a wide latitude range reaching into the southern hemisphere. 307

In the late nonlinear phase, as it would be observed by satellites farther tailward 308 along the magnetopause, vortex merging and secondary KHI develop and force recon-309 nection to occur in a wider latitudinal range. In this case the number of reconnection 310 events becomes larger in the northern hemisphere. Finally, we show a 2D chart of KH 311 vortices in the equatorial plane with reconnection line intersections, that would help in 312 discerning MLR from other kinds of *remote* reconnection events in observations. Indeed, 313 during the early nonlinear phase, particles signatures from *remote* MLR is limited in space 314 along the vortex arms, while particle signatures from lobe reconnection would intersect 315 the entire mixing region uniformly. 316

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321 References

Bavassano Cattaneo, M. B., Marcucci, M. F., Bogdanova, Y. V., Rème, H., Dandouras, I., Kistler, L. M., & Lucek, E. (2010). Global reconnection topology
as inferred from plasma observations inside kelvin-helmholtz vortices. Annales

325	<u>Geophysicae</u> , <u>28</u> (4), 893–906. doi: 10.5194/angeo-28-893-2010
326	Birn, J., Drake, J. F., Shay, M. A., Rogers, B. N., Denton, R. E., Hesse, M.,
327	Pritchett, P. L. (2001). Geospace Environmental Modeling (GEM) Magnetic
328	Reconnection Challenge. Journal of Geophysical Research: Space Physics,
329	$\underline{106}(A3), 3715 - 3719.$ doi: 10.1029/1999JA900449
330	Borgogno, D., Califano, F., Faganello, M., & Pegoraro, F. (2015, March). Double-
331	reconnected magnetic structures driven by Kelvin-Helmholtz vortices at
332	the Earth's magnetosphere. <u>Physics of Plasmas</u> , $\underline{22}(3)$, 032301. doi:
333	10.1063/1.4913578
334	Chen, X. L., & Morrison, P. J. (1990, March). Resistive tearing instability with
335	equilibrium shear flow. <u>Physics of Fluids B: Plasma Physics</u> , <u>2</u> (3), 495–507.
336	doi: 10.1063/1.859339
337	Contin, J. E. (2003). Theoretical results on the latitude dependence of the
338	Kelvin-Helmholtz instability at the dayside magnetopause for northward in-
339	terplanetary magnetic fields. <u>Journal of Geophysical Research</u> , $\underline{108}(A6)$. doi:
340	10.1029/2002JA009319
341	Daughton, W., Nakamura, T. K. M., Karimabadi, H., Roytershteyn, V., & Loring,
342	B. (2014, May). Computing the reconnection rate in turbulent kinetic lay-
343	ers by using electron mixing to identify topology. <u>Physics of Plasmas</u> , $\underline{21}(5)$,
344	052307. doi: 10.1063/1.4875730
345	Eastwood, J. P., Shay, M. A., Phan, T. D., & Øieroset, M. (2010, May). Asym-
346	metry of the ion diffusion region hall electric and magnetic fields during guide
347	field reconnection: Observations and comparison with simulations. <u>Phys. Rev.</u>
348	Lett., <u>104</u> , 205001. Retrieved from https://link.aps.org/doi/10.1103/
349	PhysRevLett.104.205001 doi: 10.1103/PhysRevLett.104.205001
350	Eriksson, S., Lavraud, B., Wilder, F. D., Stawarz, J. E., Giles, B. L., Burch, J. L.,
351	\ldots Magnes, W. (2016). Magnetospheric Multiscale observations of magnetic
352	reconnection associated with Kelvin-Helmholtz waves. <u>Geophysical Research</u>
353	<u>Letters</u> , <u>43</u> (11), 5606–5615. doi: 10.1002/2016GL068783
354	Fadanelli, S., Faganello, M., Califano, F., Cerri, S. S., Pegoraro, F., & Lavraud,
355	B. (2018, November). North-South asymmetric Kelvin-Helmholtz in-
356	stability and induced reconnection at the Earth's magnetospheric flanks.
357	Journal of Geophysical Research: Space Physics, <u>123</u> (11), 9340–9356. doi:

358	10.1029/2018JA025626			
359	Faganello, M., & Califano, F. (2017, December). Magnetized KelvinHelmholtz insta-			
360	bility: theory and simulations in the Earths magnetosphere context. $\underline{\text{Journal of}}$			
361	<u>Plasma Physics</u> , <u>83</u> (6). doi: $10.1017/S0022377817000770$			
362	Faganello, M., Califano, F., Pegoraro, F., & Andreussi, T. (2012, December). Double			
363	mid-latitude dynamical reconnection at the magnetopause: An efficient mech-			
364	anism allowing solar wind to enter the Earth\textquotesingles magnetosphere.			
365	<u>EPL (Europhysics Letters)</u> , <u>100</u> (6), 69001. doi: 10.1209/0295-5075/100/69001			
366	Faganello, M., Califano, F., Pegoraro, F., Andreussi, T., & Benkadda, S. (2012,			
367	November). Magnetic reconnection and KelvinHelmholtz instabilities at the			
368	Earth\textquotesingles magnetopause. <u>Plasma Physics and Controlled Fusion</u> ,			
369	$\underline{54}(12), 124037.$ doi: 10.1088/0741-3335/54/12/124037			
370	Faganello, M., Califano, F., Pegoraro, F., & Retinò, A. (2014, July).			
371	Kelvin-Helmholtz vortices and double mid-latitude reconnection at the			
372	Earth\textquotesingles magnetopause: Comparison between observa-			
373	tions and simulations. <u>EPL (Europhysics Letters)</u> , $\underline{107}(1)$, 19001. doi:			
374	10.1209/0295-5075/107/19001			
375	Farrugia, C. J., Gratton, F. T., Bender, L., Biernat, H. K., Erkaev, N. V., Quinn,			
376	J. M., Dennisenko, V. (1998). Charts of joint Kelvin-Helmholtz and			
377	Rayleigh-Taylor instabilites at the dayside magnetopause for strongly north-			
378	ward interplanetary magnetic field. <u>Journal of Geophysical Research: Space</u>			
379	<u>Physics</u> , <u>103</u> (A4), 6703–6727. doi: 10.1029/97JA03248			
380	Farrugia, C. J., Gratton, F. T., Gnavi, G., Torbert, R. B., & Wilson, L. B. (2014).			
381	A vortical dawn flank boundary layer for near-radial IMF: Wind observations			
382	on 24 October 2001. Journal of Geophysical Research: Space Physics, $\underline{119}(6)$,			
383	4572–4590. doi: 10.1002/2013JA019578			
384	Foullon, C., Farrugia, C. J., Fazakerley, A. N., Owen, C. J., Gratton, F. T., & Tor-			
385	bert, R. B. (2008). Evolution of Kelvin-Helmholtz activity on the dusk flank			
386	magnetopause. Journal of Geophysical Research: Space Physics, $\underline{113}(A11)$. doi:			
387	10.1029/2008JA013175			
388	Gosling, J. T., Thomsen, M. F., Bame, S. J., Elphic, R. C., & Russell, C. T. (1991).			
389	Observations of reconnection of interplanetary and lobe magnetic field lines			
390	at the high-latitude magnetopause. Journal of Geophysical Research: Space			

391	<u>Physics</u> , <u>96</u> (A8), 14097–14106. doi: 10.1029/91JA01139
392	Gratton, F. T., Gnavi, G., Farrugia, C. J., & Bender, L. (2003, October). The sta-
393	bility of the pristine magnetopause. <u>Planetary and Space Science</u> , $51(12)$, 769–
394	783. doi: 10.1016/S0032-0633(03)00113-2
395	Hasegawa, H., Fujimoto, M., Phan, TD., Reme, H., Balogh, A., Dunlop, M. W.,
396	TanDokoro, R. (2004). Transport of solar wind into Earth's magnetosphere
397	through rolled-up KelvinHelmholtz vortices. <u>Nature</u> , $\underline{430}(7001)$, 755. doi:
398	10.1038/nature02799
399	Hasegawa, H., Fujimoto, M., Takagi, K., Saito, Y., Mukai, T., & Rme, H. (2006).
400	Single-spacecraft detection of rolled-up Kelvin-Helmholtz vortices at the flank
401	magnetopause. Journal of Geophysical Research: Space Physics, $\underline{111}(A9)$. doi:
402	10.1029/2006JA011728
403	Hasegawa, H., Retinò, A., Vaivads, A., Khotyaintsev, Y., André, M., Nakamura,
404	T. K. M., Seki, Y. (2009). Kelvin-Helmholtz waves at the Earth's mag-
405	netopause: Multiscale development and associated reconnection. Journal of
406	<u>Geophysical Research: Space Physics</u> , <u>114</u> (A12). doi: $10.1029/2009$ JA014042
407	Hwang, KJ., Kuznetsova, M. M., Sahraoui, F., Goldstein, M. L., Lee, E., & Parks,
408	G. K. (2011). Kelvin-Helmholtz waves under southward interplanetary mag-
409	netic field. Journal of Geophysical Research: Space Physics, $\underline{116}(A8)$. doi:
410	10.1029/2011JA016596
411	Johnson, J. R., & Wing, S. (2009). Northward interplanetary magnetic field plasma
412	sheet entropies. Journal of Geophysical Research: Space Physics, $\underline{114}(A9)$. doi:
413	10.1029/2008JA014017
414	Johnson, J. R., Wing, S., & Delamere, P. A. (2014, November). Kelvin Helmholtz
415	Instability in Planetary Magnetospheres. <u>Space Science Reviews</u> , <u>184</u> (1), 1–31.
416	doi: 10.1007/s11214-014-0085-z
417	Kavosi, S., & Raeder, J. (2015). Ubiquity of Kelvin Helmholtz waves at Earths mag-
418	netopause. <u>Nature Communications</u> , <u>6</u> , 7019. doi: 10.1038/ncomms8019
419	Knoll, D. A., & Chacón, L. (2002, May). Magnetic Reconnection in the Two-
420	Dimensional Kelvin-Helmholtz Instability. <u>Physical Review Letters</u> , <u>88</u> (21),
421	215003. doi: 10.1103/PhysRevLett.88.215003
422	Le, G., Russell, C. T., & Gosling, J. T. (1994). Structure of the magnetopause
423	for low Mach number and strongly northward interplanetary magnetic field.

424	Journal of Geophysical Research: Space Physics, <u>99</u> (A12), 23723–23734. doi:			
425	10.1029/94JA02182			
426	Li, LX., & Narayan, R. (2004, January). Quasi-periodic Oscillations from Rayleigh-			
427	Taylor and Kelvin-Helmholtz Instability at a Disk-Magnetosphere Interface.			
428	<u>The Astrophysical Journal</u> , <u>601</u> (1), 414–427. doi: 10.1086/380446			
429	Lovelace, R. V. E., Romanova, M. M., & Newman, W. I. (2010, March). Kelvin-			
430	Helmholtz instability of the magnetopause of disc-accreting stars. <u>Monthly</u>			
431	Notices of the Royal Astronomical Society, $\underline{402}(4)$, 2575–2582. doi:			
432	10.1111/j.1365-2966.2009.16070.x			
433	Ma, X., Delamere, P., Otto, A., & Burkholder, B. (2017). Plasma Transport Driven			
434	by the Three-Dimensional Kelvin-Helmholtz Instability. Journal of Geophysical			
435	<u>Research: Space Physics</u> , <u>122(10)</u> , 10,382–10,395. doi: 10.1002/2017JA024394			
436	Matsumoto, Y., & Hoshino, M. (2004). Onset of turbulence induced by a			
437	Kelvin-Helmholtz vortex. <u>Geophysical Research Letters</u> , $\underline{31}(2)$. doi:			
438	10.1029/2003GL018195			
439	Miura, A. (1997, August). Compressible magnetohydrodynamic KelvinHelmholtz			
440	instability with vortex pairing in the two-dimensional transverse configuration.			
441	<u>Physics of Plasmas</u> , <u>4</u> (8), 2871–2885. doi: 10.1063/1.872419			
442	Miura, A., & Pritchett, P. L. (1982). Nonlocal stability analysis of the MHD			
443	Kelvin-Helmholtz instability in a compressible plasma. <u>Journal of Geophysical</u>			
444	<u>Research: Space Physics</u> , <u>87</u> (A9), 7431–7444. doi: 10.1029/JA087iA09p07431			
445	Nakamura, T. K. M., & Daughton, W. (2014). Turbulent plasma transport across			
446	the Earth's low-latitude boundary layer. Geophysical Research Letters, $\underline{41}(24)$,			
447	8704–8712. doi: $10.1002/2014$ GL061952			
448	Nakamura, T. K. M., Daughton, W., Karimabadi, H., & Eriksson, S. (2013, Septem-			
449	ber). Three-dimensional dynamics of vortex-induced reconnection and com-			
450	parison with THEMIS observations. Journal of Geophysical Research: Space			
451	<u>Physics</u> , <u>118(9)</u> , 5742–5757. doi: 10.1002/jgra.50547			
452	Nakamura, T. K. M., Eriksson, S., Hasegawa, H., Zenitani, S., Li, W. Y., Gen-			
453	estreti, K. J., Daughton, W. (2017). Mass and Energy Transfer Across the			
454	Earth's Magnetopause Caused by Vortex-Induced Reconnection. <u>Journal</u>			
455	of Geophysical Research: Space Physics, $\underline{122}(11)$, $11,505-11,522$. doi:			
456	10.1002/2017JA 024346			

457	Nakamura, T. K. M., Hasegawa, H., Daughton, W., Eriksson, S., Li, W. Y., & Naka-
458	mura, R. (2017, November). Turbulent mass transfer caused by vortex induced
459	reconnection in collisionless magnetospheric plasmas. $\underline{Nature Communications}$,
460	$\underline{8}(1), 1582.$ doi: 10.1038/s41467-017-01579-0
461	Nykyri, K., & Otto, A. (2001). Plasma transport at the magnetospheric bound-
462	ary due to reconnection in Kelvin-Helmholtz vortices. <u>Geophysical Research</u>
463	<u>Letters</u> , <u>28</u> (18), 3565–3568. doi: 10.1029/2001GL013239
464	Pritchett, L. P. (2008, 06). Collisionless magnetic reconnection in an asymmet-
465	ric current sheet. <u>Journal of Geophysical Research</u> , <u>113</u> . doi: $10.1029/$
466	2007JA012930
467	Smyth, W. D. (2003, December). Secondary KelvinHelmholtz instability in weakly
468	stratified shear flow. <u>Journal of Fluid Mechanics</u> , <u>497</u> , 67–98. doi: $10.1017/$
469	S0022112003006591
470	Song, P., & Russell, C. T. (1992). Model of the formation of the low-latitude
471	boundary layer for strongly northward interplanetary magnetic field.
472	Journal of Geophysical Research: Space Physics, <u>97</u> (A2), 1411–1420. doi:
473	10.1029/91JA02377
474	Sonnerup, B. U. Ö. (1980). Theory of the low-latitude boundary layer. Journal
475	of Geophysical Research: Space Physics, $\underline{85}(A5)$, 2017–2026. doi: 10.1029/
476	JA085iA05p02017
477	Southwood, D. J. (1968, May). The hydromagnetic stability of the magnetospheric
478	boundary. <u>Planetary and Space Science</u> , $\underline{16}(5)$, 587–605. doi: 10.1016/0032
479	-0633(68)90100-1
480	Sturner, A. P., Eriksson, S., Nakamura, T., Gershman, D. J., Plaschke, F., Ergun,
481	R. E., Burch, J. L. (2018, Feb). On multiple hall-like electron currents
482	and tripolar guide magnetic field perturbations during kelvin-helmholtz waves.
483	Journal of Geophysical Research (Space Physics), <u>123</u> (2), 1305-1324. doi:
484	10.1002/2017JA024155
485	Vernisse, Y., Lavraud, B., Eriksson, S., Gershman, D. J., Dorelli, J., Pollock,
486	C., Yokota, S. (2016). Signatures of complex magnetic topologies
487	from multiple reconnection sites induced by Kelvin-Helmholtz instability.
488	Journal of Geophysical Research: Space Physics, $\underline{121}(10)$, 9926–9939. doi:
489	10.1002/2016JA023051

Walker, A. D. M. (1981, October). The Kelvin-Helmholtz instability in the lowlatitude boundary layer. <u>Planetary and Space Science</u>, <u>29</u>(10), 1119–1133. doi:
10.1016/0032-0633(81)90011-8

Time interval	Southern h.	In-situ	Northern h.
501-525	35	81	2
526-550	377	201	7
551 - 575	677	321	327
576-600	730	268	590
601-625	544	145	686
626-650	694	247	953
651-675	488	356	1346
676-700	147	328	747
701-725	-	120	757
726-750	650	-	1656

Table 1. Number of *in-situ* and *remote* events.



Figure 1. Panel *a*: 3D rendering of KH vortices at t = 525. Blue and red colors represent plasma density (red high-density, blue low-density). The grey shaded surface, $\psi = 0$, corresponds to the magnetopause. The three central planes are perpendicular to the vortex axis. The box has been doubled along *y*-direction for sake of clearness. Panel *b*, *c*: plot of $max_{(x,y)}(|J_{\parallel}|)$ and of $max_{(x,y)}(u_{ix})$ as a function of *z* at t = 500 (dashed), t = 600 (dotted), t = 725 (continuous). Panels *d*, *e*, *f*: density iso-contours at the latitude z = 68 for three different times t = 500, t = 600and t = 725.



Figure 2. Panel a: ψ as a function of z for two chosen magnetic field lines at t = 600. Blue and red colors are set according to the plasma lines are connected to. The green line represents the magnetopause. Panel b: latitudinal distribution of connection changes at t = 525 (black), t = 600 (blue) and, finally, t = 750 (red). Panel c: time evolution of the total number of reconnected field lines (red), once (black), twice (black dashed) and 2⁺-reconnected (black dotted) lines. Panel d: time evolution of the ratio between twice-reconnected and once-reconnected lines. Panel e: time evolution of $\langle \Delta \psi^2 \rangle$, the slope 0.1 (red) is given as reference.



Figure 3. Density iso-contours at z = 0 (red high-density, blue low-density) and positions of the intersection points of the reconnected field lines in the equatorial plane (z = 0) at t = 550 (panel a) and t = 575 (panel b). In black once-reconnected lines, in purple twice-reconnected ones.