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Massive multi-mission statistical study and analytical modeling of the Earth's magnetopause: 2 - Shape and location

G. Nguyen ¹, N.Aunai ¹, B.Michotte de Welle ¹, A.Jeandet ¹, B.Lavraud ² and D.Fontaine ¹

¹CNRS, Ecole polytechnique, Sorbonne Université, Univ Paris Sud, Observatoire de Paris, Institut Polytechnique de Paris, Université Paris-Saclay, PSL Research University, Laboratoire de Physique des Plasmas, Palaiseau, France

²Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France

³Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, CNES, Toulouse, France

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Key Points:

- We use a multi-mission catalogs to provide a statistical analysis of the magnetopause location and shape.
- We confirm the expected influence of the solar wind dynamic pressure, of the IMF B_z component, of the Earth dipole tilt angle as well as the north-south asymmetry it induces.
- Varying IMF clock angle affects the level of flaring, resulting in an elliptic cross section in the cGSM YZ plane which major axis is oriented along the cGSM Y axis when the IMF is southward and along the cGSM X axis when the IMF is northward.

Corresponding author: Gautier Nguyen, gautier-mahe.nguyen@intra.edef.gouv.fr

22 **Abstract**

23 The Earth magnetopause is the boundary between the magnetosphere and the shocked
 24 solar wind. Its location and shape are primarily determined by the properties of the solar
 25 wind and interplanetary magnetic field (IMF) but the nature of the control parameters and
 26 to what extent they impact the stand-off distance, the flaring, and the symmetries, on the
 27 dayside and night side, is still not well known. We present a large statistical study of the
 28 magnetopause location and shape based on an extensive multi-mission magnetopause database,
 29 cumulating 17 230 crossings on 17 different spacecraft, from the dayside to lunar nightside
 30 distances. The results confirm the power-law dependency of the stand-off position on the
 31 solar wind pressure. The IMF clock angle itself (all amplitudes combined) does not impact
 32 the stand-off distance, nor does the cone angle. However, the magnetopause is found to
 33 move Earthward as the IMF gets stronger and more southward. All upstream conditions
 34 combined, it is found that the function used at the root of several analytical models still
 35 holds at lunar distances. We find that the equatorial flaring is larger than the meridional
 36 one. However, the meridional flaring is found to depend on the seasonal tilt conditions,
 37 being larger in the summer hemisphere. The flaring is also found to depend on the IMF
 38 clock angle. Meridional flaring increases as the IMF turns south and is then larger than
 39 the equatorial flaring. The equatorial flaring barely changes or weakly increases as the IMF
 40 turns northward, and is larger than the meridional flaring for northward conditions. The
 41 results of the study pave the way for the elaboration of a new analytical empirical expression
 42 of the magnetopause location and shape.

43 **1 Introduction**

44 The Earth’s magnetopause results from the interaction between the solar wind and
 45 the Earth magnetic field. Roughly located where the solar wind dynamic pressure and
 46 the Earth magnetic pressure balance, this current sheet marks the boundary of the Earth
 47 environment, confined from the solar wind by the frozen-in condition.

48 The first observation of the Earth magnetopause (Cahill & Amazeen, 1963), was fol-
 49 lowed by many observational and numerical studies that exhibited a strong influence of the
 50 different solar wind physical parameters on the magnetopause location and shape (Hasegawa
 51 (2012); Němeček et al. (2020) and references therein). Its first empirical and analytical
 52 modeling from Fairfield (1971) and Formisano (1979), based on the aforementioned pressure
 53 balance condition, has been done using IMP observations and a quadric surface shape.

54 From then on, several analytical empirical models parametrized by the solar wind dy-
 55 namic pressure and the IMF B_z component were developed (Roelof & Sibeck, 1993; Petrinec
 56 & Russell, 1993). These models, that continued relying on the form of a quadric surface,
 57 were fitted using ISEE magnetopause crossings and progressively considered the extension
 58 of the magnetopause in the nightside (Petrinec & Russell, 1996). With the measurements of
 59 the IMP8, ISEE 1 and ISEE 2 spacecraft used simultaneously, Shue et al. (1997) improved
 60 the accuracy of the magnetopause models by considering an inverse trigonometric function
 61 still in use in the most recent models:

$$r = r_0 \left(\frac{2}{1 + \cos(\theta)} \right)^\alpha \quad (1)$$

62 where θ is the zenith angle defined in the Appendix A, r_0 is the radial distance of the
 63 magnetopause nose and α describes the flaring of the magnetopause along the GSM X axis.

64 All of the previously mentioned models used data from spacecraft that had an equato-
 65 rial orbit and thus supposed a symmetry around the X axis. This symmetry was questioned
 66 by the investigation of Sotirelis and Meng (1999) that evidenced an influence of the Earth
 67 dipole tilt angle in accordance with the findings of Tsyganenko (1998). The influence of the

68 dipole tilt angle was later confirmed by Boardsen et al. (2000) and Eastman et al. (2000)
 69 using the Hawkeye measurements, and by the analysis of Interball data by Šafránková et
 70 al. (2002). Their observations also suggested an indentation of the magnetopause in the
 71 near-cusp region.

72 Using measurements of LANL and GOES, Kuznetsov and Suvorova (1998) evidenced
 73 the presence of a dawn-dusk asymmetry later also suggested by Dmitriev and Suvorova
 74 (1999) using an Artificial Neural Network on geosynchronous crossings. This asymmetry
 75 was later found to be linked to the aberration of the solar wind due to Earth orbital motion
 76 by Šafránková et al. (2002).

77 In the light of these new findings, Lin et al. (2010) proposed a new analytical magne-
 78 topause surface model fitted to the data, that took into consideration an azimuthal asymme-
 79 try induced by the dipole tilt angle and also kept the possibility of a dawn-dusk asymmetry
 80 despite of the correction brought to the data in order to remove the aberration.

81 Going further, Dušík et al. (2010) and Grygorov et al. (2017) used THEMIS data and
 82 pointed out that an increasing IMF B_x pulled the magnetopause sunward while the MHD
 83 simulations of Liu et al. (2015) indicated this component would rather also contribute to
 84 the north-south asymmetry already induced by the dipole tilt angle.

85 Their simulations also suggested that, for high mach numbers, increasing the IMF B_y
 86 component lead to a major axis of the magnetopause elliptic cross-section that follows the
 87 IMF orientation. This finding was also suggested at low Mach numbers by the simulations
 88 performed by (Lavraud & Borovsky, 2008; Lavraud et al., 2013) and were linked to the
 89 magnetic stress on the magnetopause that contracts it in a direction perpendicular to the
 90 IMF.

91 Despite this important number of studies, there are still numerous open questions:

- 92 1. First of all, the influence of the IMF cone angle is still unclear and the different
 93 conclusions drawn by Dušík et al. (2010) and Liu et al. (2015), that we just presented,
 94 call for further investigation.
- 95 2. Second, the influence of the IMF clock angle on the flaring has been suggested nu-
 96 merically by Liu et al. (2015) and Lavraud and Borovsky (2008). Yet, this influence
 97 still lacks of observational evidences and has not yet been considered by any empirical
 98 analytical model beyond the dependency on B_z .
- 99 3. Third, all of the magnetopause surface models considered data in the range $X >$
 100 $-40 R_e$ and are thus extrapolated to the far nightside whereas now spacecraft at lunar
 101 orbit such as ARTEMIS provide useful information on the shape of the magnetopause
 102 at these distances.
- 103 4. Fourth, different observations of the polar cusps crossings led to different conclusions
 104 regarding the shape of the magnetopause in this region. If Boardsen et al. (2000);
 105 Šafránková et al. (2002); Šafránková et al. (2005) suggested the existence of an in-
 106 dentation, Zhou and Russell (1997); Lavraud, Fedorov, et al. (2004) suggested the
 107 opposite. Eastman et al. (2000) inferred that these divergences could be explained
 108 by the definition of the magnetopause considered by each study. Using Cluster data
 109 polar cusp events, Lavraud, Phan, et al. (2004) suggested that the indentation was
 110 observed because the inner cusp boundary was considered instead of the external one
 111 associated with the kinked field lines convected tailward or sunward depending on
 112 the IMF B_z , and for which the authors noticed no specific depletion. Consequently,
 113 the question of the shape of the magnetopause in the high-altitude near-cusp region
 114 is still open and requires additional investigations.

115 In this paper, we exploit the multi-mission the magnetopause crossings catalog elab-
 116 orated with the gradient boosting developed in Nguyen et al. (2020a), one of the three
 117 companion papers of this study, to address the three first points mentioned above through a

118 statistical study of the location and shape of the magnetopause as a function of the different
 119 solar wind and IMF parameters. The results presented here will then lead to the construc-
 120 tion of a new analytical and dynamical model of the magnetopause surface as a function of
 121 relevant upstream and seasonal control parameters in the second companion paper of this
 122 study (hereafter Nguyen et al. (2020b)). The question of the indentation of the near-cusp
 123 magnetopause will then be addressed in the last companion paper of this study (hereafter
 124 Nguyen et al. (2020c)).

125 This paper is organized as follows: Section 2 presents the dataset of magnetopause
 126 crossings we use and the associated upstream solar wind and IMF conditions, Section 3
 127 focuses on the evolution of the magnetopause nose, Section 4 evidences the different mag-
 128 netopause asymmetries and Section 5 investigates the different solar wind parameters that
 129 influence the flaring level of the magnetopause.

130 2 Dataset

131 The detection of 15 062 complete magnetopause crossings made by Nguyen et al.
 132 (2020a) offers an opportunity to provide a statistical insight on various geometrical proper-
 133 ties of the magnetopause as functions of the upstream solar wind conditions. The 1 hour
 134 crossings constructed there are here reduced to 10 minutes crossings centered around the
 135 beginning of the ending time¹ of the largest magnetosheath interval detected by the region
 136 classifier. Each crossing is then associated to a set of solar wind upstream conditions ob-
 137 tained with a temporal shift of OMNI data. We determine this shift time by applying the
 138 two-step propagation algorithm presented in Šafránková et al. (2002). Using this method,
 139 we removed 772 crossings that had no available upstream solar wind condition.

140 We increase our dataset through the addition of the 2168 online² crossings of the
 141 missions IMP, ISEE, Geotail, Prognoz, Hawkeye, AMPTE, Explorer and OGO for which
 142 $X > -70$ Re, the farthest distance for which we detected ARTEMIS crossings. that were
 143 used in the comparison of Liu et al. (2015)'s model to observational data. The Hawkeye
 144 crossings were also used by Lin et al. (2010), especially when looking at the near-cusp
 145 magnetopause.

146 The combination of the two lists results in an ensemble of 17230 magnetopause cross-
 147 ings distributed on 17 different spacecraft. Contrary to the dataset presented by Wang et
 148 al. (2013), which has a similar number of crossings, the automated subset of our dataset
 149 does not consider any partial crossing, for which upstream solar wind conditions are likely
 150 to be the same. We thus expect our dataset to offer a wider range of solar wind and seasonal
 151 conditions at all altitudes and longitudes.

152 The summary of all the crossings in use in the present study and the mission they are
 153 associated with are shown in the Table 1.

154 Having merged the two lists, we correct the GSM position of each of the obtained 17230
 155 magnetopause crossings by removing the aberration due to the Earth's revolution using a
 156 similar approach as Lin et al. (2010) and Boardsen et al. (2000), assuming a revolution
 157 velocity of 30 km/s. In the following, the positions we consider will then be expressed in
 158 the so-called cGSM coordinate system.

159 The histograms of the solar wind parameters associated to the crossings are shown with
 160 the blue bins in Figure 1 and compared to the histograms of the OMNI physical parameters
 161 measured between 2001 and 2019, shown with the red bins on the same Figure. For each
 162 panel, the two distributions are similar. This indicates that the greatest part of the crossings

¹ depending on whether the crossing is unbound or outbound

² <ftp://nssdcftp.gsfc.nasa.gov/spacecraftdata/magnetopausecrossings>

| Mission | Number of Crossings | Mission | Number of Crossings |
|----------|---------------------|--------------|---------------------|
| IMP | 75 | ISEE | 333 |
| Geotail | 76 | Prognoz | 91 |
| Hawkeye | 1484 | AMPTE | 60 |
| Explorer | 17 | OGO | 32 |
| THEMIS* | 9311 | Double Star* | 891 |
| MMS* | 805 | Cluster* | 3353 |
| ARTEMIS* | 702 | Total | 17230 |

Table 1. Summary of the 17230 events that constitute our dataset. The missions denoted with an asterisk indicate the missions for which the magnetopause crossings have been obtained using the region classifier developed in Nguyen et al. (2020a).

163 occurred under normal solar wind conditions and these are the conditions under which we
 164 expect the statistics presented in this paper to be the most relevant.

165 As half of our crossings have been measured by spacecraft with relatively low apogees
 166 ($\sim 12 R_e$), it is important to make sure that our dataset is free from any orbital bias.
 167 Such limitations could indeed affect the importance of the different dependencies we will be
 168 focusing on in the next sections as discussed in Němeček et al. (2020).

169 To do so, we show in Figure 2 the projections in the $(X - Y)$ and the $(X - Z)$ plane
 170 of the crossings corrected position. The grey shading represents the time during which the
 171 different spacecraft were at given coordinates (X, Y) and (X, Z) . In both cases and for each
 172 value of X , the crossing with the highest Y or Z is located far from the maximal Y or Z
 173 reached by the spacecraft during the orbit. This suggests the crossings we selected are not
 174 limited by the orbit of the spacecraft we consider in this study.

175 This is also confirmed by Figure 3 that represents the histograms of the solar wind
 176 parameters for both the entire dataset and the crossings measured by the spacecraft that
 177 have a high apogee (above $12 R_e$). Having similar blue and red histograms for each panel
 178 ensures no orbital bias is introduced whatever solar wind parameter is considered.

179 The crossings are evenly distributed in the $(X - Y)$ plane however most of them are
 180 made at high-latitude in the northern hemisphere. We balance this distribution by adding
 181 for each crossing, its symmetric with opposite Z coordinate and tilt angle γ , in a similar
 182 way as done in Wang et al. (2013), assuming de facto that the northern summer hemisphere
 183 of the magnetopause is the symmetric the southern winter hemisphere: $r(X, Y, Z, \gamma) =$
 184 $r(X, Y, -Z, -\gamma)$.

185 In addition to the cGSM (X, Y, Z) cartesian coordinates, we will also use the spherical
 186 coordinates (R, θ, ϕ) defined following the convention presented in the Appendix A.

187 As mentioned in the introduction, the actual shape of the near-cusp magnetopause is
 188 still an open question and constitutes the main topic of Nguyen et al. (2020c) that comes as
 189 a companion paper of this study. In this study, we restrict our dataset to the 29077 crossing
 190 that are expected to occur outside of the cusp region. Following the indentation expression
 191 detailed by Lin et al. (2010), we define those so-called "out of cusp" crossings as the events
 192 for which the spherical coordinates θ and ϕ verify:

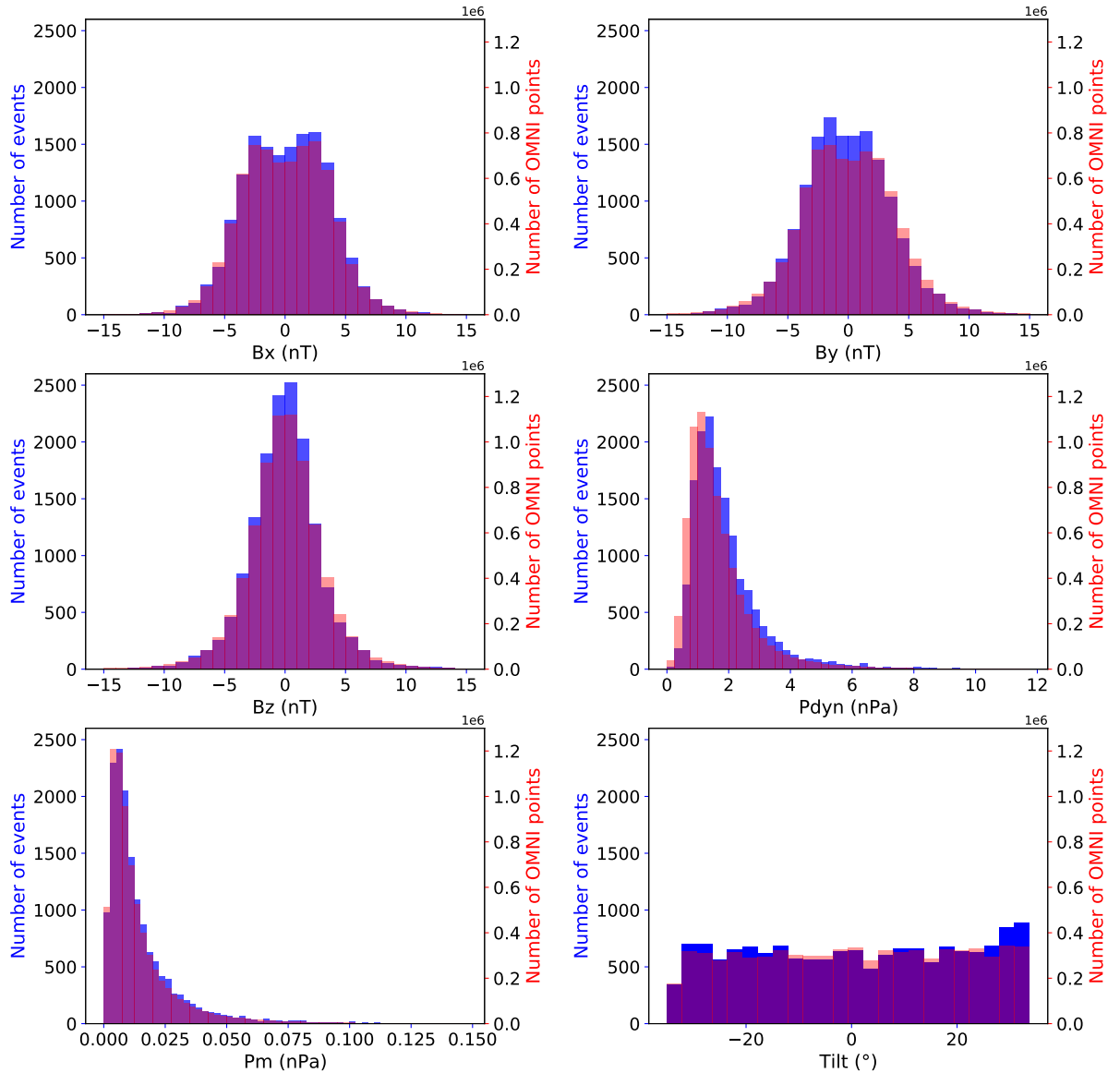


Figure 1. Statistical distribution of the solar wind parameters of the 17230 magnetopause crossings: the three magnetic field components, B_x (top left), B_y (top right), B_z (middle left), the dynamic pressure P_{dyn} (middle right), the magnetic pressure P_m (bottom left) and the dipole tilt angle (bottom right). The red bins indicate the counterpart distribution of the physical parameters of OMNI data between 2001 and 2019

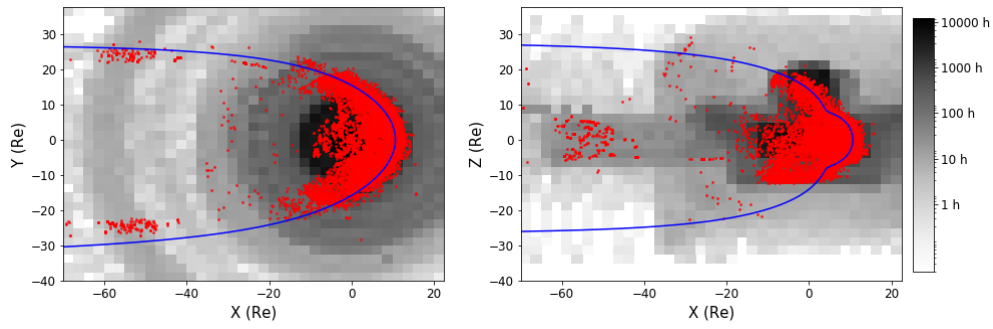


Figure 2. Projection in the $(X - Y)$ (*left*) and in the $(X - Z)$ (*right*) cGSM plane of the 17230 magnetopause crossings (red dots). The gray shading represents the time spent by all of the spacecraft in a given region of the $(X - Y)$ (resp. $(X - Z)$) plane. The blue line represents Lin et al. (2010) magnetopause model with a dynamic pressure of 2 nPa and a null B_z .

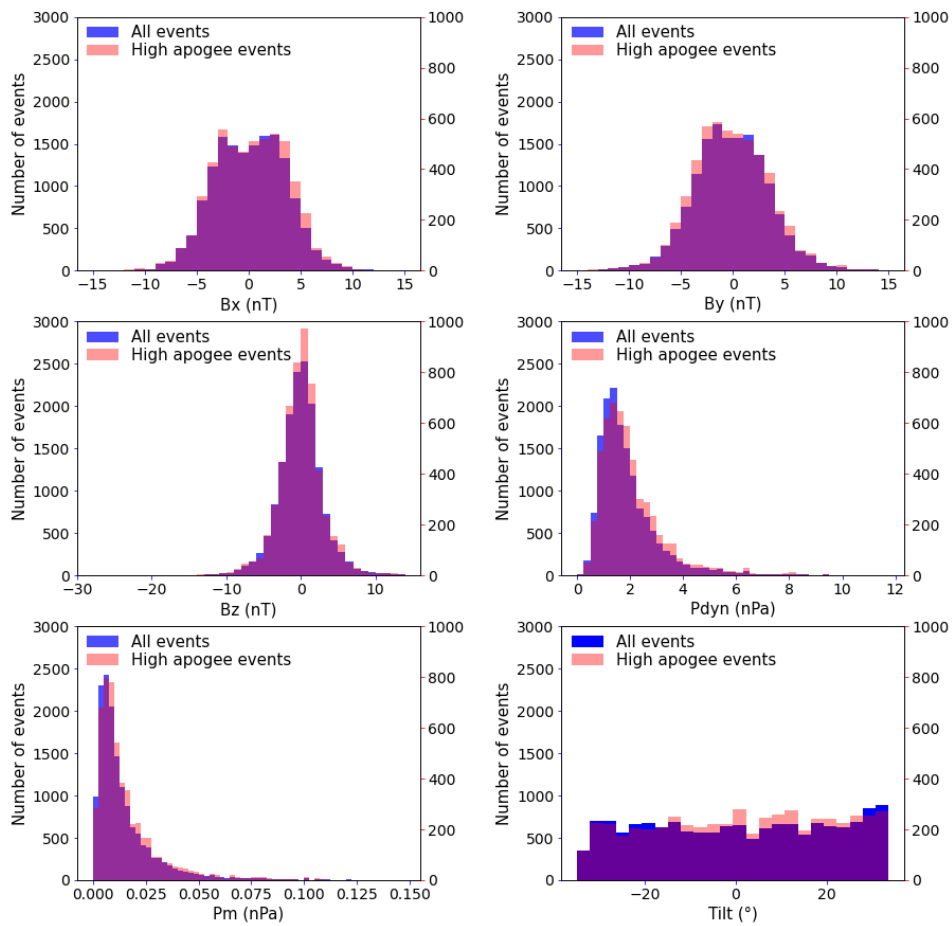


Figure 3. Histogram of the solar wind parameters of the 17230 magnetopause crossings. Each panel is the same as in Figure 1. The red here bins show the same distribution for the events measured by high apogee spacecraft.

$$\begin{cases} (\theta - \theta_n)^2 + \phi^2 \geq \left(-\frac{1}{d_n}\right)^{\frac{2}{a_{21}}} & \text{if } Z \geq 0 \\ (\theta - \theta_s)^2 + \phi^2 \geq \left(-\frac{1}{d_s}\right)^{\frac{2}{a_{21}}} & \text{if } Z \leq 0 \end{cases} \quad (2)$$

193 $d_{n,s} = a_{16} \pm a_{17}\gamma + a_{18}\gamma^2$, $\theta_{n,s} = a_{19} \pm a_{20}\gamma$, and a_{21} represent the scope, the
 194 zenithal position and the shape of the polar cusps, γ is the Earth dipole tilt angle and
 195 $a_{16} = 2.60, a_{17} = 0.832, a_{18} = -5.328, a_{19} = 1.103, a_{20} = -0.907$ and $a_{21} = 1.450$ are the
 196 corresponding coefficients fitted by Lin et al. (2010). The crossings that are found inside of
 197 this so-defined cusp-indentation will constitute the core of the dataset used in Nguyen et al.
 198 (2020c).

199 3 The magnetopause subsolar stand-off distance

200 We study the magnetopause subsolar stand-off distance by selecting the 300 events
 201 for which $\theta < 7.50^\circ$ and $Z > 0$ and approximate the magnetopause stand-off distance r_0 of
 202 these crossings by their actual radial distance r .

203 Naturally, we expect the total pressure $P_{dyn} + P_m$ to be the feature that has the
 204 greatest influence on the subsolar stand-off distance. Figure 4 represents the radial distance
 205 of the subsolar events subset as a function of the total pressure. The stand-off distance r_0
 206 here appears to have a clear and consistent power-law dependency on the total pressure.
 207 This was already exhibited in observations by Shue et al. (1997) and numerically by Liu et
 208 al. (2015). We exhibit this dependency by fitting r_0 to the power law $a_0(P_{dyn} + P_m)^{a_1}$. The
 209 result of this fit is represented by the solid blue line and the grey interval that represents
 210 the 1-sigma confidence interval. The obtained values of a_0 and a_1 are shown in the top right
 211 corner of the Figure. a_0 represents the stand-off distance at 1 nPa and the obtained value
 212 is thus consistent with the typical value we expect for the subsolar magnetopause. We also
 213 find an exponent value of -0.161 for a_1 , which is very close to the theoretical $-\frac{1}{6}$ and close
 214 to the values obtained by Shue et al. (1997), Lin et al. (2010) and Liu et al. (2015).

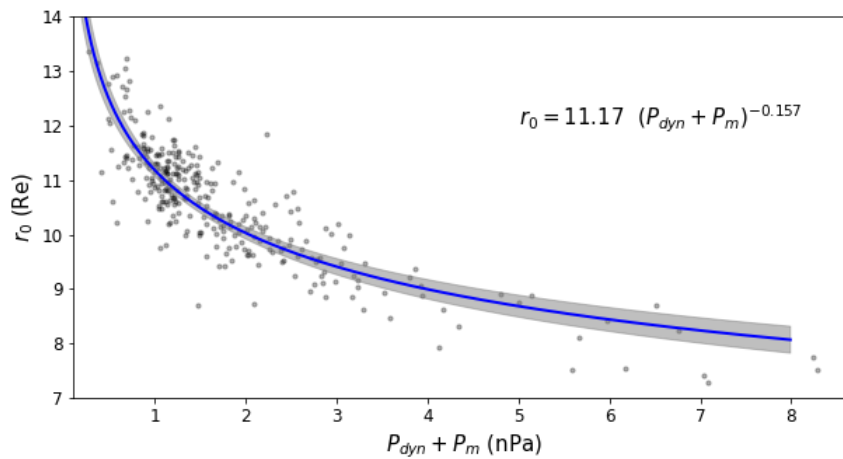


Figure 4. Variations of r_0 with the dynamic pressure. The solid blue line represent the fit of r_0 as a power-law of $P_{dyn} + P_m$ and the grey interval is the 1-sigma confidence interval of such fit.

215 The dependency on the solar wind ram and magnetic pressure is so strong that studying
 216 now the dependency of the standoff distance on the IMF orientation must be done with care.

217 To cope with it, we separate the 300 events into 30° wide bins of IMF cone (resp. clock)
 218 and fit r_0 as a power law of $(P_{dyn} + P_m)$ for each bin. We limit the bins for each angle by
 219 looking at the total number of each event per defined bin. This still offers a wide range of
 220 upstream IMF conditions of the same order as the ones used in the studies led by Roelof
 221 and Sibeck (1993) and Petrinec and Russell (1993).

222 We represent the evolution of the fitted stand-off distance at 1 nPa, the so-defined a_0 ,
 223 as a function of the IMF cone and clock angles with the black circles in the two panels of
 224 Figure 5.

225 Concerning the influence of the cone angle, first, we notice a small increase of a_0 as
 226 the IMF becomes more radial. This evolution is consistent with the findings of Dušík et al.
 227 (2010) or Grygorov et al. (2017) but in our case the effect an order of magnitude fainter.
 228 Their larger motion may be coming from their much broader angular selection, which may
 229 confuse flaring effects with the stand-off distance evolution. In both our case or theirs,
 230 the sunward motion is in the error bars of analytical models in that region and call for
 231 more future more detailed investigations. For now, as this influence appears to be negligible
 232 compared to the one of the total pressure, we will not consider it in the rest of the study.

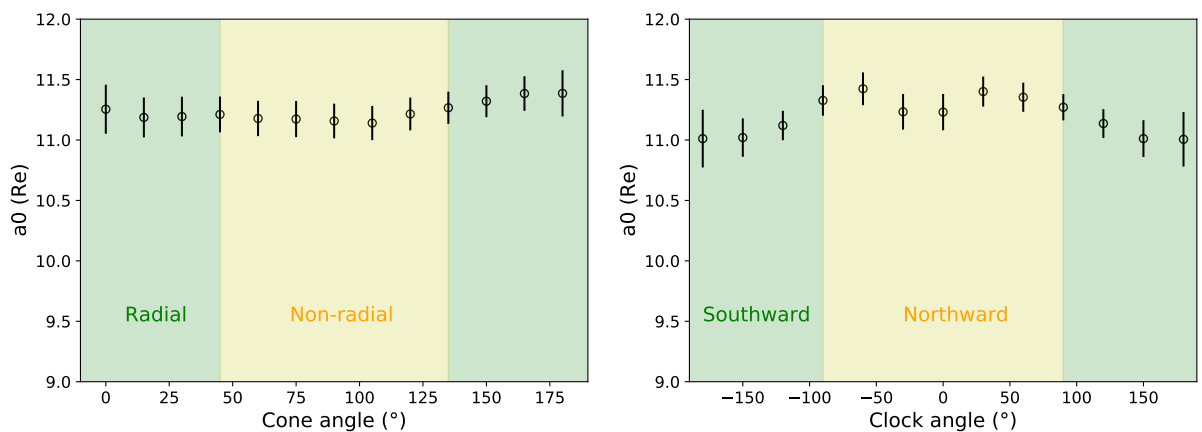


Figure 5. Evolution of the stand-off distance at 1 nPa, a_0 as a function of the IMF cone (*left*) and clock (*right*) angles. The black circles represent the value we obtain from fitting a power law to r_0 for different cone (resp. clock) angle bins. The error bars represent the 1-sigma confidence interval of such fits.

233 Concerning now the clock angle, the fits suggest an earthward motion of the magne-
 234 topause when the IMF turns from a northward to a southward orientation. Such motion
 235 is consistent with the picture of a subsolar magnetopause eroded by magnetic reconnection
 236 under a southward IMF. The motion could also be the consequence of a stronger Earthward
 237 magnetic force due to the enhanced magnetopause current in southward IMF. Whatever its
 238 cause, this motion barely stands out of the error bars and appears negligible compared to
 239 the one induced by the solar wind pressure to really consider the IMF clock angle actually
 240 has an influence on the magnetopause subsolar stand-off distance.

241 The clock angle does apparently not change a_0 . However, it acts as a switch. Combined
 242 with an increasing IMF amplitude the clock orientation of the IMF can now indeed change
 243 a_0 significantly, as shown in the evolution of a_0 as a function of B_z on Figure 6. Here, the
 244 noticed decrease of a_0 for negative B_z is also consistent with the explanations given above.
 245 Those arguments may also explain the saturation of a_0 for positive B_z since magnetic

246 reconnection is not thought to occur and the magnetic shear is expected to be low at low
 247 latitude for a northward IMF.

248 For comparative purposes, the three colored dashed lines represent the evolution of
 249 a_0 with B_z previously obtained by Shue et al. (1997) (green line and equation 11 of the
 250 aforementioned paper), Lin et al. (2010) (red line and equation 20 of the aforementioned
 251 paper) and Liu et al. (2015) (blue line and equation 4 of the aforementioned paper). For
 252 northward IMF, the values of a_0 is consistent with the one obtained by both Shue et al.
 253 (1997) and Liu et al. (2015) while Lin et al. (2010)'s model over-estimates the stand-off
 254 distance by 2 Re. The three models also predict an earthward motion of the magnetopause
 255 for southward IMF and the slope of the decrease of a_0 for negative B_z is close from the one
 256 exhibited by Shue et al. (1997).

257 The studies of Liu et al. (2015) and Shue et al. (1997) suggest a saturation of a_0 for
 258 strong negative B_z (not shown in Figure 6) that confirms the observations made by Yang et
 259 al. (2002). In our case, even if the decrease of our fitted values of a_0 for negative B_z appears
 260 to be less important below -7 nT, the large error bars for this point and the restricted range of
 261 B_z values, due to the restriction of our dataset to the subsolar magnetopause, do not permit
 262 to draw any conclusion on what happens for extreme values of B_z . Subsolar magnetopause
 263 crossings under extreme B_z are extremely scarce and it is then of no use to study them
 264 from a statistical point of view for now. They however constitute excellent samples for
 265 further case studies on the behavior of the magnetosphere under extreme conditions, such
 266 as Interplanetary Coronal Mass Ejections.

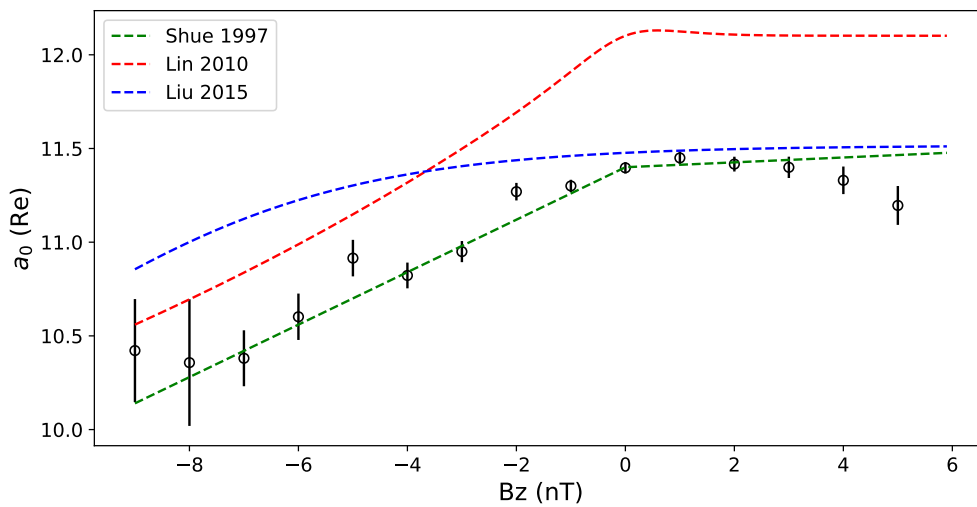


Figure 6. The same than Figure 5 but as a function of the IMF B_z . The three colored dashed line represent the evolution of a_0 according three previous existing models: Shue et al. (1997) (*green*), Lin et al. (2010) (*red*) and Liu et al. (2015) (*blue*).

We can use the two evolutions we exhibited to establish a primary empirical expression of the magnetopause stand-off distance in the form:

$$r_0 = \alpha_0 (1 + \alpha_2 \tanh(\alpha_3 B_z + \alpha_4)) (P_{dyn} + P_m)^{-\alpha_1} \quad (3)$$

267 Applying the Levenberg-Marquardt algorithm (Newville et al., 2014) to our 300 sub-
 268 solar crossings, we determine the values of the 5 α_i and then obtain:

$$r_0 = 10.91 (1 + 0.039 \tanh (0.65 B_z + 2.0)) (P_{dyn} + P_m)^{-0.153} \quad (4)$$

269 **4 Asymmetries**

270 The first empirical models (Fairfield, 1971; Formisano, 1979; Petrinec & Russell, 1993;
 271 Shue et al., 1997) of the magnetopause shape and location assumed axisymmetry around
 272 the cGSM X axis. Nevertheless, the MHD simulations of Lu et al. (2011) evidenced an
 273 asymmetry between the magnetopause flaring in the $(X - Y)$ plane and the flaring in the
 274 $(X - Z)$ plane. They evidenced the IMF B_z component and the Earth dipole tilt angle as
 275 the main actors at the origin of such azimuthal asymmetry. This asymmetry was considered
 276 by the models of Wang et al. (2013) and Lin et al. (2010) and already observed (Šafránková
 277 et al., 2002) but never confirmed in the far nightside, below -20 Re.

278 We address this question by selecting on one hand the 2047 events for which $|Y| < 2 R_e$
 279 (the so-called $X - Z$ plane events) and on the other hand the 5443 events for which $|Z| < 1 R_e$
 280 (the so-called $X - Y$ plane events). In both cases, we represent $\log(r)$, the radial distance
 281 of each crossing as a function of $\log\left(\frac{2}{1+\cos(\theta)}\right)$, the inverse trigonometric function especially
 282 considered by the models of Shue et al. (1997) and Liu et al. (2015), in the two panels
 283 of Figure 7. In both cases, we notice a linear dependency that legitimates this analytic
 284 expression. It is also worth noting that the linear dependency holds for the far nightside
 285 crossings of ARTEMIS giving in the process credit to using such an analytical expression.

286 The slope of a fitted linear expression should give a first estimate of the flaring coef-
 287 ficient α in both the $(X - Z)$ and the $(X - Y)$ planes. The red curve and the associated
 288 grey shading confidence intervals are shown in the two panels of Figure 7. We find a value
 289 of α that is lower in the $(X - Z)$ plane than in the $(X - Y)$ plane. Even if we lack obser-
 290 vational evidences for the magnetopause at high latitude in the far nightside, this suggests
 291 the existence of an azimuthal asymmetry and a magnetopause that is more elongated in the
 292 Y-direction than in the Z-direction.

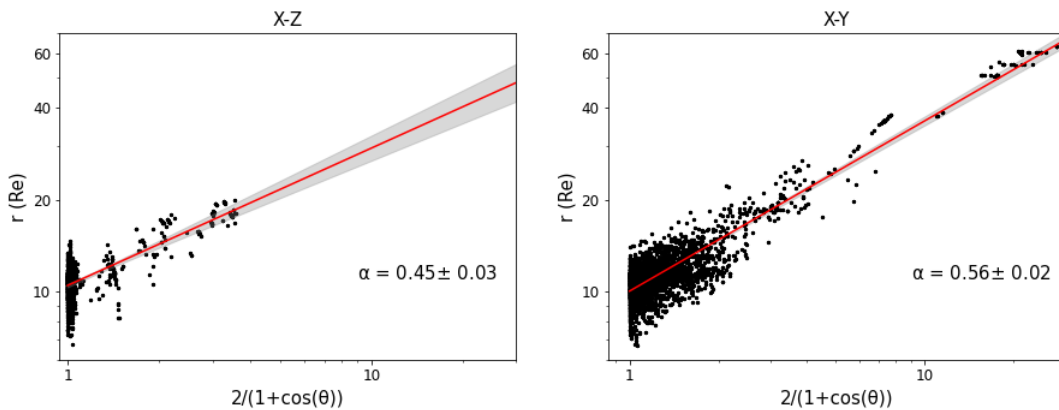


Figure 7. Evolution of the radial distance r of the crossings in the $(X - Z)$ (left) plane and in the $(X - Y)$ plane as a function of the inverted trigonometric function $\frac{2}{1+\cos(\theta)}$ on a logarithmic scale. The solid red line represent the linear fit of $\log r$ as a function of $\frac{2}{1+\cos(\theta)}$. The grey intervals represent the confidence intervals of such fits.

293 In addition to the azimuthal asymmetry, the MHD simulations of Liu et al. (2012)
 294 showed the dipole tilt angle induced a North-South asymmetry that was also observed by
 295 Boardsen et al. (2000) and considered by the fits of Lin et al. (2010) and Wang et al. (2013).

296 The symmetrization of the dataset that was done in section 2 allows this asymmetry and
 297 the evolution of the northern (or the southern) magnetopause flaring with the dipole tilt
 298 angle will be evidenced and investigated in the next subsection.

299 Following what we did to evidence the azimuthal asymmetry, we now separate the
 300 5170 crossings located in the so-defined $(X - Y)$ plane into 3028 dawnward ($Y < 0$) and
 301 2415 duskward ($Y > 0$) events and apply the same method as previously. The logarithm
 302 of the radial distance r of these two subsets of events as a function of the logarithm of the
 303 inverted trigonometric function $\frac{2}{1+\cos(\theta)}$ is shown in the Figure 8.

304 In this case, we obtain almost equal values for α on both sides, indicating no apparent
 305 dawn-dusk asymmetry and thus, a symmetric magnetopause regarding the $Y = 0$ plane. In
 306 the light of those results, we decide to add another symmetry to the dataset by reverting
 307 the Y coordinate, increasing the size of the out of cusps crossings from 31671 to 63344.

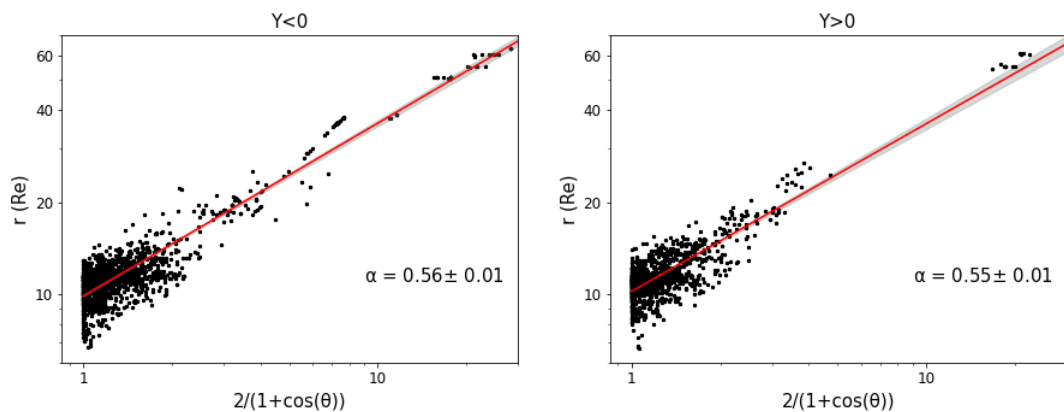


Figure 8. The same figure than 7 but with the crossings in the $Y < 0$ (*left*) and in the $Y > 0$ (*right*) half-spaces.

308 5 Magnetopause flaring

309 Figures 7 and 8 provide evidence of the magnetopause flaring as the power law of an
 310 elliptic function consistently with the equation 1. They also show a different flaring α in
 311 the $(X - Y)$ and in the $(X - Z)$ directions, indicating the necessity to treat the influence
 312 of the various solar wind parameters in the two planes separately.

313 5.1 Influence of the dynamic pressure

314 Following our previous results, we now symmetrize the dataset in the Y direction. We
 315 focus on the equatorial flaring by selecting the 5443 duskward events for which $|Z| < 1 R_e$
 316 and on the polar flaring by selecting the 4064 northern events for which $|Y| < 2 R_e$. We
 317 represent the averaged distribution of the total pressure in these two newly defined $(X - Y)$
 318 and $(X - Z)$ planes in the two panels of Figure 9.

319 Although the observation is noisier in the left panel, one can see the appearance of clear
 320 parallel contours which intercept goes from 15 R_e to 7 R_e with an increasing pressure. This
 321 proves that the main effect of an increasing pressure stands in an earthward translation of
 322 the magnetopause along the X axis and thus, that the flaring coefficient of the magnetopause
 323 is independent from the upstream solar wind pressure. This finding is consistent with Lin
 324 et al. (2010) who found no particular pressure dependency and with the results of Liu et al.

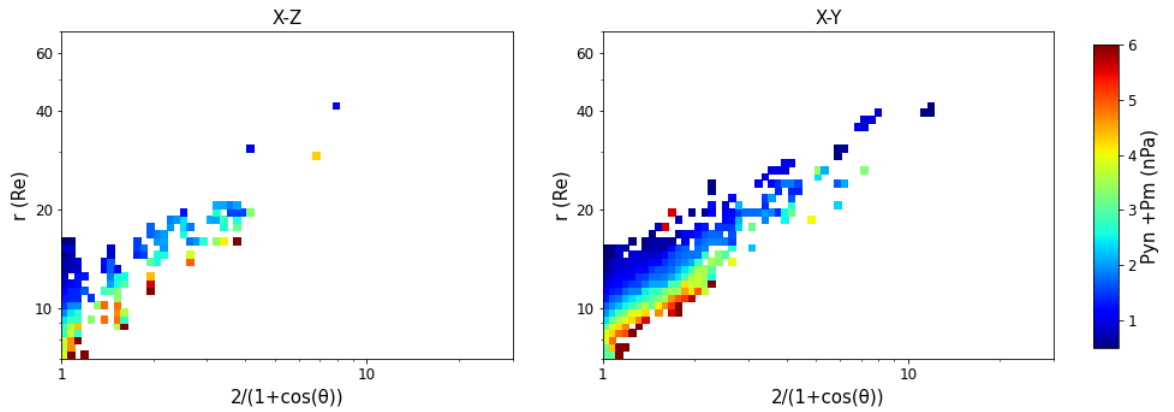


Figure 9. Averaged spatial distribution of the solar wind total pressure ($P_{dyn} + P_m$) associated to the crossings in the ($X - Z$) (*left*) and in the ($X - Y$) (*right*) planes.

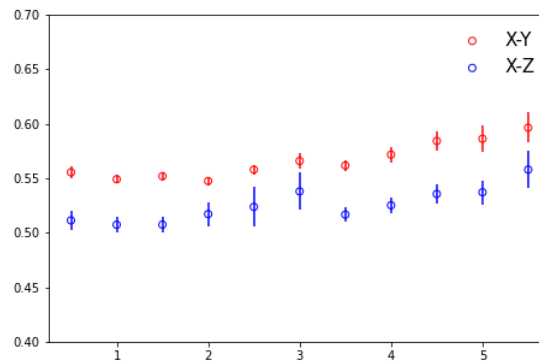


Figure 10. Evolution of the fitted flaring coefficient α as a function of the total pressure for the out of cusps crossings in the ($X - Y$) (*blue*) and in the ($X - Z$) (*red*) planes. The error bars represent the 1-sigma confidence intervals of the different fits.

325 (2015) and Shue et al. (1997) who found a flaring coefficient that had very little variations
 326 with the pressure.

327 Another method we have to evidence this independence consists in separating the data
 328 of each plane into sliding pressure bins between 0.5 and 6 nPa and estimating the flaring
 329 coefficient α by fitting the radial position of the crossings to the equation 1 with r_0 being
 330 defined by the equation 4. The result of such fits is shown in the two planes in Figure 10
 331 and seeing very little variations of α in the two planes confirms the independence.

332 5.2 Influence of the dipole tilt angle

333 The dipole tilt angle is expected to only influence the ($X - Z$) flaring of the mag-
 334 netopause ((Boardsen et al., 2000; Lin et al., 2010) and references therein). Thus, we
 335 investigate the influence of the dipole tilt angle on the flaring by considering the ($X - Z$)
 336 crossings previously defined only. As for the case of pressure, we separate the crossings into
 337 sliding 12.5° tilt angle bins and estimate α for each group of events.

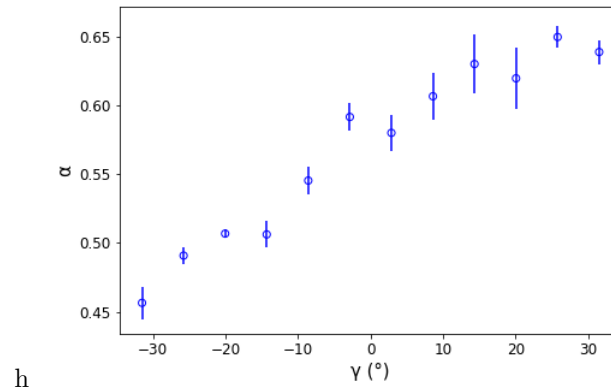


Figure 11. Evolution of the fitted flaring coefficient α as a function of the dipole tilt angle γ for the out of cusps crossings in the $(X - Z)$ plane. The error bars represent the 1-sigma confidence intervals of the different fits

338 The results of the fits are shown in the Figure 11 and shows a clear linear increase of
 339 α with an increasing γ . This indicates a northern hemisphere magnetopause that has an
 340 increased flaring during summer.

341 This finding is consistent with the dependencies evidenced by Boardsen et al. (2000)
 342 and Lin et al. (2010) and very close from the hyperbolic tangent dependency chosen by Liu et
 343 al. (2015). Having a symmetrized dataset, the observed flaring for the southern hemisphere
 344 will naturally also be a linear function of γ with the same intercept but an opposite slope.

345 5.3 Influence of the IMF clock angle

346 The influence of the IMF orientation on the magnetopause shape was first noticed by
 347 Aubry et al. (1970) who noticed, using Ogo 5 measurements, an earthward motion of the
 348 boundary when the IMF was southward. The phenomena was later-on frequently found in
 349 numerous statistical studies of the magnetopause location and shape (Sibeck et al., 1991;
 350 Petrinec & Russell, 1996) and considered in the most recent analytical models through the
 351 dependence on the IMF B_z component for both the subsolar stand-off distance and the level
 352 of flaring (Shue et al., 1997; Lin et al., 2010; Liu et al., 2015; Wang et al., 2013).

353 The aforementioned models all suggested the cross-section of the magnetopause in the
 354 YZ plane would be an ellipse which major axis points in the cGSM Z direction when the
 355 IMF points due south.

356 Such behaviour might be explained by the erosion mechanism resulting from magnetic
 357 reconnection and usually described by the so-called *onion peel model* Sibeck et al. (1991).
 358 When the IMF points south, the so-believed equatorial X-line leads to a tailward convection
 359 of the reconnected flux. This may increase the XZ flaring in the process, although on average
 360 should be somewhat balanced by tail reconnection in a steady Dungey cycle. This increase
 361 would stop as the IMF becomes northward, a condition for which lobe reconnection will
 362 lead to dayside convection, possibly decreasing the XZ flaring down to a point where the
 363 major axis of the YZ magnetopause cross-section points along Y.

364 It is also worth noting that the influence of the IMF orientation might depend on
 365 the value of the Alfvén Mach Number. Using MHD simulations, Lavraud and Borovsky
 366 (2008) suggested that, at low Mach numbers, resulting in lower magnetosheath plasma β ,
 367 the magnetic force contracts the magnetopause so that its YZ elliptic cross-section now has

368 a major axis along Z for both due south and due northward IMF while eastward (resp.
 369 westward) IMF rotates the major axis anti-clockwise (resp.clockwise). This twisting of the
 370 magnetopause with the clock angle as also been reported by (Liu et al., 2015). It however
 371 introduces an asymmetry with respect to the XZ plane which we have not found on average
 372 and thus ignored in the current study. We will thus only focus on XZ and XY flarings.

373 We now investigate the influence of the IMF clock angle Ω . We consider the events in
 374 the $(X - Y)$ (resp. $(X - Z)$) plane and separate them into 30° (resp. 60°) wide clock angle
 375 bins between -180° and 180° and estimate α for each group of events. The obtained values
 376 are shown in the Figure 12.

377 For southward IMF orientations (green shaded intervals), the $(X - Z)$ flaring, repre-
 378 sented by the blue dots, is higher than the equatorial flaring represented with the red dots.
 379 The major axis of the magnetopause YZ cross-section is then oriented along the cGSM Z
 380 axis. For northward orientations (yellow-shaded intervals), the $(X - Z)$ flaring decreases and
 381 now becomes lower than the equatorial one, which increases a bit but overall varies less. This
 382 evolution is consistent with the suggestions of the other existing empirical magnetopause
 383 models (Shue et al., 1997; Lin et al., 2010; Liu et al., 2015; Wang et al., 2013) and could
 384 thus possibly be explained by the erosion mechanism triggered by magnetic reconnection.
 385 The current study limits the investigation to the $(X - Z)$ and $X - Y$ planes for statisti-
 386 cal reasons, further investigations should focus on assessing whether the magnetopause is
 387 actually twisted as suggested by both Liu et al. (2015) and Lavraud and Borovsky (2008).
 388 Additionally, our results suggest different magnetopause cross-section for due southward and
 389 northward IMF orientations, which is different from the suggestions made by Lavraud and
 390 Borovsky (2008). This might be due to the fact our results are obtained with no distinction
 391 between the low and the high Alfvén Mach number and it would thus be interesting, in a
 392 further study, to investigate if the result we evidenced still hold for low Alfvén Mach number
 393 values.

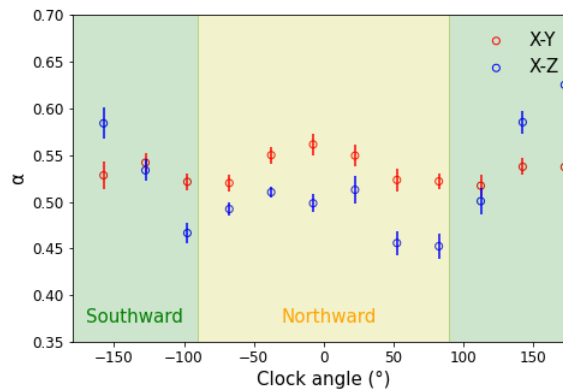


Figure 12. Evolution of the fitted flaring coefficient α as a function of the IMF clock angle for the out of cusps crossings in the $(X - Y)$ (blue) and in the $(X - Z)$ (red) planes. The green intervals indicate the intervals where the IMF is southward and the yellow interval is the interval of northward IMF. The error bars represent the confidence intervals of the different fits.

394 The flaring coefficients evolves with the IMF clock angle. This suggests a dependence
 395 on the IMF B_y component. To assess this, we consider the 890 events in the $(X - Z)$
 396 plane for which $1 \text{ nT} < B_z < 3 \text{ nT}$ and the 772 events in the $(X - Z)$ plane for which
 397 $-3 \text{ nT} < B_z < -1 \text{ nT}$. In the two cases, we separate the events into 1 nT wide $|B_y|$ bins
 398 and estimate α for each group of events. The obtained values are shown in the Figure 13.

399 For a negative B_z (green dots), increasing the absolute value of B_y results in a de-
 400 creasing flaring coefficient. By contrast, the $(X - Z)$ flaring stays roughly constant or
 401 mildly increases as $|B_y|$ increases for a positive B_z . These evolutions are consistent with
 402 the evolution of α with the clock angle, as shown in the Figure 12.

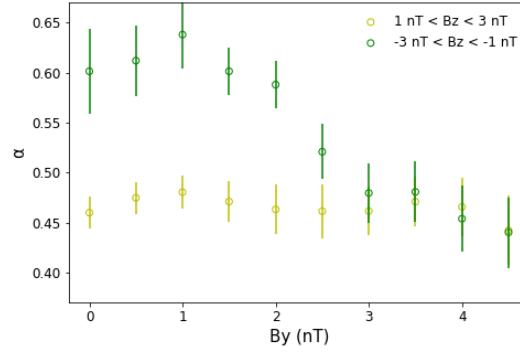


Figure 13. Evolution of the fitted flaring coefficient α as a function of the IMF $|B_y|$ component for the out of cusps crossings in the $(X - Z)$ plane for which $1 \text{ nT} < B_z < 3 \text{ nT}$ (yellow) and for which $-3 \text{ nT} < B_z < -1 \text{ nT}$ (green). The error bars represent the confidence intervals of the different fits.

403 5.4 Primary expressions of the flaring coefficient

404 Following what was done with r_0 , the influences of both the Earth dipole tilt angle
 405 and the IMF clock angle can be translated into primary empirical analytical expressions
 406 describing the magnetopause flaring in the $(X - Y)$ and in the $(X - Z)$ planes.

407 Applying the Levenberg-Marquardt fitting method to the 5443 events of the $(X - Y)$
 408 plane, we obtain:

$$\alpha = 0.56 + 0.015 \cos(\Omega) \quad (5)$$

409 In a similar manner, the same method applied to the 2047 events of the $(X - Z)$ plane
 410 leads us to:

$$\alpha = 0.5 + 0.016\gamma - 0.05 \cos(\Omega) \quad (6)$$

411 Naturally, these two expressions can be generalized to all azimuthal angle ϕ through
 412 the fit of the general expression of the magnetopause surface function (1) to the entire
 413 symmetrized dataset. This issue is addressed in the second companion paper of our study
 414 (Nguyen et al., 2020b).

415 6 Conclusion

416 In this paper, we conducted a statistical study on the magnetopause location and
 417 shape, based on the combination of the automatically detected multi-mission crossings of
 418 Nguyen et al. (2020a) and older crossings accessible online. In particular, we have investi-
 419 gated how the stand-off distance and the equatorial and meridional flaring depend on the
 420 solar wind pressure and IMF clock angle.

421 Our findings can be summarized as follows:

- 422 1. The stand-off distance depends on the solar wind (dynamic and magnetic) pressure as
 423 a power law which exponent is found very close to the theoretical $-1/6$, consistently
 424 with previous studies such as Šafránková et al. (2002); Shue et al. (1997); Lin et al.
 425 (2010); Liu et al. (2015).
- 426 2. The stand-off distance decreases with as the IMF becomes more strongly southward,
 427 the model describes by Shue et al. (1997) matches this variation better than other
 428 models.
- 429 3. The radial position of the magnetopause is well described by the inverse trigonometric
 430 function proposed by Shue et al. (1997) up to lunar distances.
- 431 4. We found no particular influence of the IMF cone angle component on the stand-
 432 off distance. The sunward motion suggested by Grygorov et al. (2017) as B_x gets
 433 stronger is thus not found. It however appeared to be of order of model errors in
 434 that region. Further investigation is needed to clarify the possible dependency of the
 435 magnetopause flaring on the cone angle.
- 436 5. The clock angle is found to influence the flaring of the magnetopause, not only via
 437 the B_z component, but also via the B_y one. The equatorial ($X - Y$) flaring is roughly
 438 constant or weakly increases for northward IMF. The ($X - Z$) meridional flaring
 439 however strongly increase as the IMF turns south. For these southward IMF, the
 440 ($Y - Z$) cross-section of the magnetopause is well described by an ellipse which major
 441 axis points along Z . For northward cases however, the decrease of the meridional
 442 ($X - Z$) flaring and the weak increase of the equatorial ($X - Y$) flaring make the
 443 ellipse more elongated in the Y direction. Although further detailed investigations are
 444 needed to understand the physical effects at the root of these observations, they are
 445 consistent with a picture where reconnection carries flux into the lobe in southward
 446 conditions, leading to periods of larger ($X - Z$) flaring. For statistical reasons, we
 447 limited our study to the ($X - Y$) and ($X - Z$) planes and symmetrized our dataset,
 448 thereby excluding the question of the continuous magnetopause twisting with the
 449 IMF as suggestion by Liu et al. (2015) and Lavraud and Borovsky (2008). Future
 450 investigations, using more data, should address this delicate point.

451 These different findings pave the way to the construction of a new asymmetric mag-
 452 netopause shape and location model. This issue will be addressed in Nguyen et al. (2020b)
 453 that comes as a companion paper of this study.

454 Finally, this study was performed on the magnetopause crossings outside of the cusp
 455 region and thus gives elements to three of the issues mentioned in the introduction: the
 456 influences of the IMF cone and clock angle and the behavior of the magnetopause in the
 457 far nightside. It would be interesting to give a specific insight on the near-cusp crossings of
 458 our dataset to figure out the actual existence or absence of indentation of the magnetopause
 459 in this region. This last issue will be addressed in the third companion paper of our study
 460 Nguyen et al. (2020c).

461 Appendix A Spherical coordinates

462 We define the spherical equivalent (R, θ, ϕ) of the cartesian GSM coordinates (X, Y, Z)
 463 according to the Figure A1. $R = \sqrt{X^2 + Y^2 + Z^2}$ is the radial distance from the center of
 464 the Earth, θ is the zenith angle between the direction of R and the X axis and the azimuth
 465 ϕ is the angle between the projection of R in the $Y - Z$ plane and the positive direction of
 466 the Z axis:

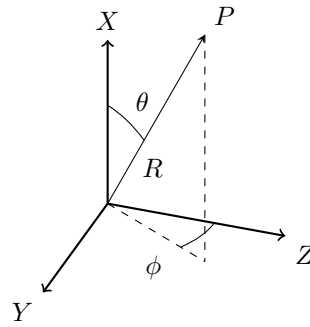


Figure A1. Representation of the spherical equivalent of the cartesian GSM coordinates used in this paper.

$$X = R \cos(\theta) \tag{A1}$$

$$Y = R \sin(\theta) \sin(\phi) \tag{A2}$$

$$Z = R \sin(\theta) \cos(\phi) \tag{A3}$$

467

Acknowledgments

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Enter acknowledgments, including your data availability statement, here.

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