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1 Multi-spacecraft observation of magnetic cloud erosion by 2 magnetic reconnection during propagation

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21

22 **Abstract.** During propagation, Magnetic Clouds (MC) interact with their
23 environment and, in particular, may reconnect with the solar wind around it,
24 eroding away part of its initial magnetic flux. Here we quantitatively analyze
25 such an interaction using combined, multi-point observations of the same MC
26 flux rope by STEREO A, B, ACE, WIND and THEMIS on November 19-20,
27 2007. Observation of azimuthal magnetic flux imbalance inside a MC flux
28 rope has been argued to stem from erosion due to magnetic reconnection at its
29 front boundary. The present study adds to such analysis a large set of
30 signatures expected from this erosion process. (1) Comparison of azimuthal
31 flux imbalance for the same MC at widely separated points precludes the
32 crossing of the MC leg as a source of bias in flux imbalance estimates. (2) The
33 use of different methods, associated errors and parametric analyses show that
34 only an unexpectedly large error in MC axis orientation could explain the
35 azimuthal flux imbalance. (3) Reconnection signatures are observed at the MC
36 front at all spacecraft, consistent with an on-going erosion process. (4)
37 Signatures in suprathermal electrons suggest that the trailing part of the MC
38 has a different large-scale magnetic topology, as expected. The azimuthal
39 magnetic flux erosion estimated at ACE and STEREO A corresponds
40 respectively to 44% and 49% of the inferred initial azimuthal magnetic flux
41 before MC erosion upon propagation. The corresponding average
42 reconnection rate during transit is estimated to be in the range 0.12-0.22
43 mV/m, suggesting most of the erosion occurs in the inner parts of the
44 heliosphere. Future studies ought to quantify the influence of such an erosion
45 process on geo-effectiveness.

47 1. Introduction

48 The interplanetary manifestations of solar coronal mass ejections, called interplanetary
49 coronal mass ejections (ICMEs), are magnetized plasma structures that play a pivotal role
50 in solar-terrestrial interaction [Gosling 1993; Wimmer Schweingruber et al., 2006;
51 Borovsky and Denton, 2006; Foullon et al., 2007; Gopalswamy et al., 2007; Lavraud and
52 Borovsky, 2008; Möstl et al., 2010; Richardson and Cane, 2010]. These structures may
53 interact in various ways with the ambient solar wind during their propagation in the
54 interplanetary medium [Burlaga et al., 1987; Farrugia et al., 1997]. Magnetic clouds, a
55 subset of ICMEs, are primarily characterized by a large smooth rotation of enhanced
56 magnetic field, low temperature and low plasma beta [Burlaga et al., 1981; Klein and
57 Burlaga, 1982]. The large-scale structure of a MC consists of a twisted magnetic flux rope
58 [Goldstein, 1983; Marubashi, 1986; Burlaga, 1988; Lepping et al., 1990]. Another
59 signature commonly associated with ICMEs is the presence of counterstreaming
60 suprathermal electrons [Gosling et al., 1987; Farrugia et al., 1993] which indicates a large-
61 scale “closed” magnetic topology, with magnetic field lines rooted on the Sun at both ends.

62 Magnetic reconnection converts magnetic energy into thermal and kinetic energy.
63 Although this process has been mainly studied in situ in Earth’s magnetosphere, signatures
64 of magnetic reconnection have previously been associated with magnetic clouds [Farrugia
65 et al., 2001] and confirmed recently as ubiquitous in the solar wind [Gosling et al., 2005a;
66 2006a; Davis et al., 2006; Phan et al., 2006; Huttunen et al., 2008; Lavraud et al., 2009;
67 Eriksson et al., 2009]. Gosling et al. [2005a; 2006a] identified Petschek-like reconnection
68 exhausts characterized by bifurcated current sheets. These current sheets form a pair of
69 rotational discontinuities with correlated changes in the components of the magnetic field
70 and flow velocity on one side and anti-correlated changes on the other. Magnetic
71 reconnection implies a change in magnetic field topology. This can be diagnosed using
72 suprathermal electron characteristics since they travel extremely fast along the magnetic
73 field. Unidirectional electron beams of a few hundred eV (called the “strahl”) are
74 associated with regular solar wind, i.e., open field lines connected to the hot coronal source
75 at one end. Counterstreaming suprathermal electrons, in addition to being observed inside
76 ICMEs [e.g., Shodhan et al., 2000], have been measured in narrow reconnection exhaust at
77 the Heliospheric Current Sheet (HCS). This is also a result of the newly closed nature of
78 the magnetic field lines in the specific configuration of the HCS [Gosling et al., 2006b;
79 Lavraud et al., 2009] if the spacecraft is crossing the exhaust Sunward of the reconnection
80 line along the magnetic field. By contrast, a spacecraft crossing the exhaust anti-Sunward
81 of the reconnection line observes a lack of strahl electrons in both the parallel and anti-
82 parallel directions [Gosling et al., 2005b]. Note that other suprathermal electron signatures
83 have been reported [e.g. Gosling et al., 2002; Steinberg et al., 2005; Wimmer-
84 Schweingruber et al., 2006; Skoug et al., 2006; Foullon et al., 2009; Lavraud et al., 2010].

85 During its propagation in the interplanetary medium, a MC may interact with the solar
86 wind around it. Magnetic reconnection may in particular occur at the front of the MC,
87 thereby leading to a global topological change as depicted in Figure 1. Figure 1 presents the
88 expected magnetic structure as an observing spacecraft would cut through either a non-
89 eroded (panel a) or eroded MC (panel c). Dasso et al. [2006] presented a new method to
90 analyze the structure of a MC that consists in calculating the azimuthal magnetic flux
91 accumulated along the spacecraft trajectory. An imbalance in accumulated azimuthal flux,
92 with an excess flux at the back of the MC, is believed to be the signature of magnetic
93 erosion at its front (cf. section 4 for further explanations). This possibility has further been
94 studied using both observations [Dasso et al., 2007; Möstl et al., 2008] and global MHD
95 simulations [Schmidt and Cargill, 2003; Taubenschuss et al., 2010]. The simulation works
96 showed in particular that the efficiency of the reconnection process increases with the

97 relative velocity of the MC with respect to the ambient solar wind.

98 ICMEs are major sources of strong southward interplanetary magnetic field and often
99 increased solar wind flow speed impinging on the Earth's magnetosphere. The subsequent
100 coupling and geomagnetic storms, mediated in its most part through magnetic reconnection
101 at the dayside magnetopause [Dungey, 1961; Akasofu, 1981], are directly related to the
102 intensity of the magnetic field in MCs and their sheath regions. Because the proposed
103 erosion directly alters the amount and duration of the typically large magnetic flux
104 contained within MCs impinging on Earth, this process may significantly impact the geo-
105 effectiveness of MCs over the solar cycle. Evaluation of MC magnetic flux budget is also
106 very relevant to the study of coronal processes during eruption [Qiu *et al.*, 2007]. For
107 instance, MC flux estimations are important for comparison with the magnetic flux
108 observed in the suspected solar source region, and which may be used to link MCs to their
109 solar origin [e.g. Mandrini *et al.*, 2005; Nakwacki *et al.*, 2011]. It is thus important to take
110 into account the presumed eroded flux when comparing in situ and solar observations of
111 MCs.

112 Finally, it should be noted that we use a twisted flux rope hypothesis for our MC in the
113 present study [e.g., Burlaga, 1981]. Although this hypothesis appears justified from the
114 results of our multi-spacecraft analysis, MCs have also been described using writhed and
115 sheared three-dimensional magnetic field or spheromak-shaped structures [e.g. Al Haddad
116 *et al.*, 2011; Vandas *et al.*, 1993].

117 Here we study an event that occurred on November 19-21, 2007. The MC was observed
118 by STEREO A (ST-A), STEREO B (ST-B), ACE, WIND and THEMIS in particular.
119 Several authors have studied this event in other contexts [Gosling and Szabo, 2008;
120 Farrugia *et al.*, 2011; Kilpua *et al.*, 2011; Howard and Tappin, 2009], as will be discussed
121 in section 5. The purpose of the present study is to demonstrate the occurrence of magnetic
122 flux erosion by magnetic reconnection at the front of this MC, owing to its interaction with
123 the slow solar wind ahead of it, using a combination of different methods and signatures
124 together with detailed error assessments. In section 3, we describe data observed by ST-A,
125 ST-B, ACE, WIND and THEMIS. In section 4 we present the different methods used and
126 associated results. We discuss these results in section 5.

127 2. Instrumentation

128 The solar terrestrial relations observatory (STEREO) [Kaiser *et al.*, 2008] consists of two
129 spacecraft that slowly drift ahead (referred to ST-A) and behind (referred to ST-B) the
130 Earth on similar orbits around the Sun. The mission was designed to study the solar activity
131 stereoscopically and the structure of the solar wind. We use data from the two Solar Wind
132 Electron Analysers (SWEA) [Sauvaud *et al.*, 2008] and magnetometers (MAG) [Acuña *et al.*
133 *et al.*, 2008] from the In-situ Measurement of Particles and CME Transient (IMPACT)
134 instrument suite [Luhmann *et al.*, 2008]. Proton data from the PLASTIC instrument [Galvin
135 *et al.*, 2008] are also utilised. These instruments are identical onboard each of the two
136 STEREO spacecraft. The time resolutions are 3 seconds and 1 minute for magnetic field
137 and velocity, respectively.

138 In addition, we make use of measurements from the Advanced Composition Explorer
139 (ACE) spacecraft [Stone *et al.*, 1998], in particular data from the Solar Wind Electron,
140 Proton, Alpha Monitor investigation (SWEPAM) [McComas *et al.*, 1998] and magnetic
141 field (MAG, 3-sec resolution) [Smith *et al.*, 1998]. Due to the low time resolution of ACE
142 velocity moments (1-min resolution), we also use THEMIS-B magnetic field and plasma
143 data (3-sec resolution for both datasets) from the fluxgate magnetometers (FGM) [Auster *et al.*
144 *et al.*, 2008] and the electrostatic analyzers (ESA) [McFadden *et al.*, 2008].

145 We work mainly in the RTN coordinate system. This system is centred on the
146 spacecraft, \mathbf{R} is the sun-to-spacecraft unit vector, \mathbf{T} is perpendicular to it and points in the
147 direction of planetary/spacecraft orbital motion, \mathbf{N} completes the right-handed triad. In
148 Figure 10, we use the Heliocentric Earth Ecliptic (HEE) coordinate system where \mathbf{X} is the
149 Sun-Earth line direction, \mathbf{Z} is directed towards the North Pole relative to the ecliptic plane
150 and \mathbf{Y} closes a right-handed system. Electron pitch angle distributions (PADs) at 250 eV
151 are used for ST-A and ST-B. ACE electron PADs are from the 272 eV channel.

152 3. Overview of the event

153 The MC under study was observed at 4 main locations: ST-A, ST-B, ACE (L1), and
154 THEMIS (near-Earth environment) (Figure 2). At this time, ST-A and ST-B were separated
155 by $\sim 40^\circ$ (respectively $\sim 20^\circ$ west and east from Earth).

156 Figure 3 shows data from ST-B, ACE, and ST-A. The panels are the same for each
157 spacecraft. The first panel shows the traditional suprathermal electron PAD spectrograms,
158 while the second panel shows the same data but normalised (between 0 and 1) for each
159 sample in time. This allows a better visualisation of PAD characteristics when the dynamic
160 range of fluxes is large. The following panels show ion and magnetic field data in the same
161 format for each spacecraft. The magnetic cloud at ST-B is more complex, we thus first
162 describe below the data from ACE and ST-A.

163 The magnetic cloud front and back boundaries at ACE are defined at 22:22 UT (Nov.
164 19) and 11:42 UT (Nov. 20). The magnetic field is high and shows a clear smooth rotation
165 over a large angle inside the MC (panel j). Based on magnetic field data alone, *Gosling and*
166 *Szabo* [2008] marked the start of the MC at 23:32 UT (Nov. 19) at WIND (corresponding
167 to 23:13 UT at ACE). Based on the magnetic field, plasma and electron PAD data,
168 however, we believe the MC front is observed earlier, at 22:22 UT at ACE (cf. section
169 4.1.4). Both fronts are marked in Figure 3. Note, however, that this choice does not affect
170 the results regarding azimuthal flux imbalance as discussed in the following sections (the
171 amount of azimuthal flux between these two fronts is small compared to the flux rope
172 magnetic flux, about 5%).

173 Panel h shows the proton temperature and density for ACE. From 22:22 UT (19 Nov.) to
174 11:42 UT (20 Nov.), the proton temperature is lower than in the ambient solar wind, again
175 as expected for a MC. The velocity (panel i) is relatively constant, ~ 460 km/s, until 11:42
176 UT (20 Nov.), only about 70 km/s faster than the solar wind ahead of it. The solar wind
177 velocity enhances significantly after the MC, highlighting the presence of a high speed
178 stream just adjacent and following the MC.

179 At ACE, before 21:21 UT on 19 November the electron PAD shows a 180° strahl
180 (toward sector) (panel f and g). Just after this time, the PAD becomes field-aligned (0°),
181 indicative of the crossing of the HCS. Counterstreaming electrons appear at 22:22 UT on
182 19 November implying closed magnetic field lines at the beginning of the MC. From 4:05
183 UT to 11:42 UT on 20 November, the spectrogram shows unidirectional PADs again; this
184 interval includes essentially the entire second-half (trailing) of the MC.

185 The duration of the MC at ST-A is longer than at ACE. The MC is characterized by
186 enhanced magnetic field and a clear large-scale rotation of that field between 22:00 UT (19
187 Nov.) to 3:20 UT (21 Nov.) (panel o). ST-A observes bidirectional suprathermal electrons
188 from 22:00 UT (19 Nov.) to 12:00 UT (20 Nov.) (panel k and l). Unidirectional electrons
189 are yet observed in the trailing part from 12:00 UT (20 Nov.) to the end of the MC at 3:20
190 UT (21 Nov.). Unlike at ACE, no HCS crossing is observed before the MC. The MC
191 appears to have replaced the HCS at ST-A.

192 At ST-B, the time period 22:47 UT (19 Nov.) - 7:00 UT (20 Nov.) shows a somewhat

193 lower proton temperature with an enhanced and rotating magnetic field consistent with
 194 signatures of MCs (panel c), apart from a relatively extended and complex region in its
 195 middle around 3:00 UT (20 Nov.). Suprathermal electron PADs are mostly unidirectional
 196 and in the same direction as at ACE and ST-A (panel a and b), consistent with ST-B
 197 sampling the same MC. Based on various in-situ properties, the event at ST-B has been
 198 identified as the same event as observed at ACE and ST-A [Farrugia *et al.*, 2011; Kilpua *et*
 199 *al.*, 2011].

200 4. Method and erosion signatures

201 To determine whether magnetic erosion occurs through magnetic reconnection at the
 202 front of the MC, we here explore several methods and signatures.

203

204 4.1 Magnetic flux imbalance estimation

205 4.1.1 The direct method of Dasso *et al.* [2006]

206 We first employ the “direct method” developed by Dasso *et al.* [2006]. This method
 207 consists in calculating and analysing the accumulated azimuthal magnetic flux along the
 208 spacecraft trajectory in the MC frame. The accumulative flux per unit length is defined as:

$$209 \frac{F_y(x)}{L_{in}} = \int_{t_{in}}^{t(x)} B_{y,cloud}(t') * V_{x,cloud} dt' \quad (1)$$

210

211 Here t_{in} is the time of the MC front boundary. B_y and V_x are the respective components
 212 of the magnetic field and velocity from the observed time series in the MC frame. We use
 213 the frame as defined in Dasso *et al.* [2006]. In the RTN coordinate system, the latitude
 214 angle θ ($[-90^\circ, 90^\circ]$) is defined between the ecliptic plane and the cloud axis (called \mathbf{z}_{cloud}).
 215 The longitude angle φ ($[-180^\circ, 180^\circ]$) is defined as the angle between the projection of the
 216 axis in the ecliptic plane and the Sun-spacecraft direction. The direction \mathbf{d} is defined by the
 217 rectilinear trajectory of the spacecraft ($-\mathbf{x}_{rtm}$), \mathbf{y}_{cloud} is in the direction $\mathbf{z}_{cloud} \times \mathbf{d}$ and \mathbf{x}_{cloud}
 218 completes the right-handed orthonormal base ($\mathbf{x}_{cloud}, \mathbf{y}_{cloud}, \mathbf{z}_{cloud}$). This frame is depicted in
 219 Figure 1.

220 Figure 1 shows an idealized schematic of the expected magnetic configuration for both
 221 non-eroded (panel a) and eroded (panel c) MCs, together with the associated variation in
 222 each magnetic field component (panels b and d). For non-eroded MCs (panel a), the
 223 magnetic field azimuthal component B_y (blue curve) is symmetric about the MC center.
 224 Starting the integration of the B_y component at the leading MC boundary, the accumulated
 225 azimuthal magnetic flux (red curve) goes back to a null value exactly at the MC trailing
 226 boundary. If the MC is eroded (panel c) the expected topological changes alter the variation
 227 of the azimuthal B_y component. The accumulated azimuthal magnetic flux is then
 228 unbalanced: it goes back to a null value before the end of the MC, revealing what Dasso *et*
 229 *al.* [2006] called a “back region”. The back region thus corresponds to an excess of
 230 azimuthal magnetic flux whose counterpart at the front of the MC has been eroded through
 231 magnetic reconnection.

232

233 4.1.2 Determination of the MC orientation using Minimum Variance Analysis

234 Knowledge of the cloud axis orientation is the prime quantity needed to apply this
 235 method. To that end, we use two different methods: minimum variance analysis (MVA)
 236 [Sonnerup *et Cahill*, 1967] and force-free MC fitting [Lepping *et al.*, 1990]. With MVA,
 237 the cloud axis is determined by the intermediate eigenvector [Bothmer and Schwenn,
 238 1998]. We apply MVA to normalized magnetic field vector time series in order to avoid the
 239 influence of fluctuations in magnetic field magnitude [Gulisano *et al.*, 2007].

240 In order to assess potential errors on MC axis orientations from MVA, we apply a
 241 bootstrap method [Kawano and Higuchi, 1995] with 1000 random resamplings of the
 242 magnetic field data acquired inside the MC. This resampling is used to quantify the impact
 243 of the intrinsic variability of the dataset on the results. We then repeat this for 7 different
 244 nested time intervals within the MC separated by 10 minutes: we begin each of the 7 time
 245 intervals 10 minutes after the previous and end it 10 minutes before. This enables us to
 246 estimate how errors related to the definition of the MC boundaries may affect the resulting
 247 axis orientation. Since such sub-intervals containing a properly defined MC should lead to
 248 the same axis determination through MVA, this approach allows us to assess errors from
 249 possible sub-structures in the MC (for example, compressions at the edges). Note that for
 250 the analysis at ACE, although we consider the leading boundary at 22:22 UT on 19
 251 November for the accumulated azimuthal flux balance estimates, we only apply MVA after
 252 23:13 UT owing to unusual fluctuations of the magnetic field during the interval 22:22-
 253 23:13 UT.

254

255 4.1.3 Determination of the MC orientation using force-free MC fitting

256 The second method to determine the MC axis orientation and other parameters is a flux
 257 rope fitting (FRF) based on a force-free model with least-square minimisation. The force-
 258 free model satisfies the equation $\nabla \times B = \alpha B$ [Goldstein, 1983; Marubashi, 1986], with $\alpha =$
 259 constant [Burlaga, 1988; Lepping et al., 1990]. Lundquist [1950] gave the solution for a
 260 cylindrical geometry in an axially symmetric configuration:

261

$$\begin{aligned}
 & \text{(radial)} & B_r &= 0 \\
 & \text{(azimutal)} & B_\varphi &= B_0 J_1(\alpha r) \\
 & \text{(axial)} & B_z &= B_0 J_0(\alpha r)
 \end{aligned} \tag{2}$$

262

266 Here J_n is the Bessel function of the first kind of order n , B_0 is the strength of the
 267 magnetic field at the MC axis and r is the radial distance from the axis. The constant α
 268 determines the magnetic field twist of the flux tube. To apply this method, we estimate
 269 initial guesses of the following parameters in the MC frame determined by MVA: the
 270 helicity (right or left handed), the MC axis orientation (the latitude angle θ and longitude
 271 angle φ), and the impact parameter p (distance between the centre of the flux tube and the
 272 spacecraft trajectory through the MC, which is approximated for initial guess as $\langle B_x \rangle / \langle B \rangle$
 273 (where B_x is computed in the MC frame previously obtained from MVA [Démoulin and
 274 Dasso, 2009]). Then, we apply a least square fitting method and a first series of iteration to
 275 determine the angle θ and φ . When these are determined, we perform another series of
 276 iteration to determine the impact parameter p and α .

277

278 It is worth mentioning that the MC is compressed at its rear edge by a high-speed solar
 279 wind. This restrains its expansion, as shown by a rather constant speed throughout the MC
 280 at all spacecraft. Hence we do not take the MC expansion into account for both MC fitting
 281 and analysis of magnetic flux imbalance (cf. next section). Nakwacki et al. [2008] have
 282 shown, anyway, that radial expansion does not strongly affect such calculation.

282

283 4.1.4 Results on magnetic flux imbalance

284

285 Table 1 summarizes the results obtained from the above analyses. The accumulative
 286 azimuthal magnetic flux per unit length F_y/L , which starts at the front MC boundary, is
 287 shown in Figure 4 for ST-B, ACE, and ST-A. The solid colored curves show the results
 288 obtained for each of the 7 nested time intervals to which MVA is applied (from the full
 289 interval, in purple, to the smallest interval in red), and the 1000 curves observed for each
 color correspond to the results from the bootstrap resamplings. These curves thus highlight

290 the errors, or variability, of the azimuthal flux accumulation results. The dashed lines show
291 the result using the axis orientation given by the FRF method at each spacecraft. In Table 1,
292 the time of flux balance is given for each spacecraft and for both methods used: FRF and
293 MVA (for MVA analysis the time corresponds to the mean of the 7000 colored curves)

294 Despite a large set of trials in error assessment and the use of different methods, there is
295 a clear imbalance in flux in every case for both ST-A and ACE. The more complex case of
296 ST-B does not show a clear signature of potential magnetic erosion (Figure 4). This stems
297 from the unusual magnetic structure that is observed between 02:00 and 04:00 UT on 20
298 November. This structure impacts on the results of MC axis orientation from MVA and
299 FRF, and thus the magnetic flux balance analysis is possibly biased.

300 We now report some additional tests that are not shown. We performed a second series
301 of analyses where we modified the time interval used (for both MVA and FRF) so as to
302 exclude the back region from the analysis. Indeed, if the MC is asymmetric owing to
303 erosion, the back region constitutes a region of additional flux with no counterpart on the
304 front side of the MC. Although such asymmetry might influence the results from both
305 MVA and FRF (and in turn the flux balance analysis), the use of a shortened MC interval at
306 ACE without the back region yielded results compatible with erosion and with those
307 obtained when the full MC is analysed. The analysis at ST-A using a shortened MC
308 interval without the back region also shows flux imbalance with similar results, but there is
309 substantially less variability in the results when the back region is removed from analysis.
310 Indeed, we note that our MVA analyses yield weak standard deviations in terms of axis
311 orientation at ACE: lower than 2° . At ST-A, the standard deviation is $\sim 6^\circ$ if the full MC is
312 analysed (Figure 4) and $\sim 2^\circ$ (not shown) if the back region is removed from analysis. These
313 results are consistent with the work carried out by *Gulisano et al.* [2007] who studied the
314 bias of MVA in the determination of MC axis orientation. They concluded that the
315 orientation is well determined for MC axes close to the ecliptic plane and with reasonably
316 small impact parameters (i.e., spacecraft crossing close to the MC centre) as in the present
317 case.

318 As mentioned in section 3, we defined the front MC boundary at 22:22 UT (19
319 November) at ACE, which is earlier than the corresponding start time given in *Gosling and*
320 *Szabo* [2008] and *Farrugia et al.* [2011] for WIND. Although not shown, quite obviously if
321 one starts the azimuthal flux accumulation in Figure 4 at the later time defined by these
322 authors, then the estimated back region is even more extended ($\sim 5\%$ change in total
323 azimuthal flux).

324 In conclusion, for both ACE and ST-A the combination of several methods and error
325 analyses based on both bootstrap and changes in the MC boundary definitions all concur
326 and are compatible with the existence of a significant excess magnetic flux in the trailing
327 part of the MC, which we further substantiate and interpret in the next sections.

328 In order to estimate the amount of azimuthal magnetic flux that was eroded from the
329 front of the MC, we compute the total azimuthal flux before reconnection with the ambient
330 solar wind magnetic field ($F_{t,azimuthal}$), which can be determined using solely the second half
331 of the MC from the sum of F_y/L (in absolute value) between the peak in accumulated flux
332 and the end of the MC (Figure 4) [*Dasso et al.*, 2006]. We assume a MC length of ≈ 2 AU
333 in order to be consistent with previous works [e. g. *Nackwacki et al.*, 2011]. We obtain
334 $F_{t,azimuthal} = 3.36 \times 10^{21}$ Mx for ACE and 5.42×10^{21} Mx for ST-A. The amount of eroded
335 azimuthal flux $F_{e,azimuthal}$ (i.e., equal to the azimuthal flux contained in the inferred back
336 region) is then given by the absolute value of F_y at the end of the MC, $F_{e,azimuthal}$
337 $= 1.48 \times 10^{21}$ Mx at ACE and 2.68×10^{21} Mx at ST-A. The eroded azimuthal magnetic flux
338 corresponds to 44% and 49% of the total, initial azimuthal magnetic flux, respectively at
339 ACE and ST-A

340 With regards to the axial magnetic flux F_z , we may also calculate it from observations as
 341 performed in *Dasso et al.* [2006, 2007]. We assume a circular MC cross section, $p=0$ and
 342 we compute $r = x(t) - x_{center}$ (x is the distance inside the MC in AU, x_{center} corresponds to the
 343 center of the MC as defined by the maximum in accumulated azimuthal B_y magnetic field)
 344 Note that we also neglect the axial flux in the core since it only corresponds to a correction
 345 of the order $(p/R)^2$ [*Dasso et al.*, 2006]. Following *Dasso et al.* [2006; 2007], the axial flux
 346 is calculated as:

$$347 \quad F_z = 2\pi \int_{t_{in}}^{t(x)} B_{z,cloud}(t')(x(t') - x_{center}) V_{x,cloud}(t') dt'$$

348 From this calculation we obtain the total axial magnetic fluxes, which are $F_{t,axial} = 0.64$
 349 $\times 10^{21}$ Mx at ACE and 0.69×10^{21} Mx at ST-A. We also find eroded axial magnetic fluxes
 350 of $F_{e,axial} = 0.48 \times 10^{21}$ Mx at ACE and 0.31×10^{21} Mx at ST-A. Hence, the amounts of
 351 eroded axial magnetic fluxes correspond to 75% and 45% of the total axial fluxes,
 352 respectively at ACE and ST-A.

353

354 **4.2 Parametric study of axis orientation impact on accumulated azimuthal flux**

355 Figure 5 shows a parametric study that highlights the amount of eroded azimuthal
 356 magnetic flux as a function of MC axis orientation. Each contour value quantifies the
 357 inferred erosion (as defined in Section 4.1.4) when alternative MC orientations are
 358 arbitrarily chosen in terms of latitude and longitude at ACE (a) and ST-A (b). The central
 359 value corresponds to the mean MC axis orientation from our analysis (cf. Table 1).

360 Figure 5 demonstrates that only a large error in axis determination (more than 20° for
 361 ST-A and more than 10° for ACE), and specifically towards lower latitude only, could
 362 explain the imbalance in azimuthal flux. This simple parametric study further and strongly
 363 supports the fact that there is an actual azimuthal flux imbalance at both ACE and ST-A,
 364 and which we interpret as the signature of magnetic erosion.

365

366 **4.3 Signatures of magnetic reconnection at the MC front boundary**

367 The erosion mechanism investigated here implies the occurrence of magnetic
 368 reconnection at the front of the MC during its propagation. Magnetic reconnection creates
 369 rotational discontinuities that are observed as bifurcated current sheets bounding an exhaust
 370 [*Farrugia et al.*, 2001; *Gosling et al.*, 2005a; *Gosling and Szabo*, 2008]. During an exhaust
 371 crossing, a spacecraft should observe correlated changes in \mathbf{V} and \mathbf{B} components at one
 372 edge (or current sheet) of the exhaust and anti-correlated changes at the other edge.

373 Figure 6 shows selected plasma and magnetic field data at different spacecraft when
 374 these cross the front boundary of the MC on 19 November. Vertical dashed green lines
 375 identify the transition from the solar wind ahead of the MC (to the left) to the MC itself (to
 376 the right). As shown by these lines, there are fairly clear bifurcated current sheet signatures
 377 (two well separated gradients mainly in either/or the B_t and B_n components) at the three
 378 spacecraft shown: ST-B, THEMIS-B, and ST-A. Note that we use THEMIS-B data here
 379 because this dataset has a higher time resolution (3 sec) than ACE (1-min for velocity
 380 moments) and because WIND has a data gap at this time. THEMIS B is in the pristine solar
 381 wind (as confirmed from visual inspection of the particle energy-time spectrograms) close
 382 to Earth at this time (GSE coordinates $[-9, -29, -9.5] R_E$). To confirm that these bifurcated
 383 current sheet signatures are bounding reconnection exhausts, i.e., with Alfvénic changes in
 384 the velocity components, we perform the Walén test [*Hudson et al.*, 1970; *Paschmann et*
 385 *al.*, 1986]:

386

$$387 \quad V_{pre} = V_{ref} \pm \rho_{ref}^{1/2} \times (B / \rho - B_{ref} / \rho_{ref}) / \mu_0^{1/2} \quad (3)$$

388

389 Here, V , B , ρ , represent the velocity, magnetic field and density (the pressure anisotropy
390 factor is not accounted here owing to the lack of such data). The subscript “ref” denotes the
391 reference time at the leading or trailing edge of the exhaust in the upstream region, and
392 subscript “pre” denotes the velocity predicted across the region for an exhaust bounded by
393 rotational discontinuities. The positive (negative) sign is chosen for the trailing (leading)
394 edge of the exhaust. The velocities predicted inside the exhausts are shown as colored
395 dashed lines in Figure 6 for ST-A and THEMIS-B. (For context, Figure 7 shows data only
396 around the exhaust seen at ACE and THEMIS-B, confirming it is indeed the same exhaust
397 observed by THEMIS-B at 23:18 UT (Nov. 19). Moreover, we note that despite the low
398 resolution of the proton velocity data at ACE, the expected velocity change (marked “jet”
399 in Figure 7) is also seen at this spacecraft. Based on the velocity at the MC front
400 (~ 440 km/sec) and the distance between ACE and THEMIS (~ 224 Re) the expected delay is
401 ~ 54 min, compatible with observations.

402 In Figure 6 the Walén tests are performed inward from the vertical black dashed lines,
403 which correspond to the reference times used in the application of Equation (1). As can be
404 seen, the test is basically successful for both THEMIS-B and ST-A. From Figure 6, we note
405 the exhausts at THEMIS-B and ST-A have very different durations. The spatial width of
406 the exhaust is estimated to be 9450 km at THEMIS-B, whereas at ST-A it is 6.1×10^5 km.
407 This suggests that ST-A is at a significant distance from the reconnection line while
408 THEMIS-B (and ACE) is much closer. For ST-B, a bifurcated current sheet structure akin
409 to that observed at ACE and THEMIS-B is observed at $\sim 22:46$ UT (November 19).
410 However, the time resolution of the proton data is insufficient to perform the Walén test at
411 this spacecraft because the exhaust is much thinner at ST-B than at ST-A.

412 Because the magnetic field component normal to a reconnecting current sheet should be
413 constant for an ideal magnetic reconnection exhaust with a constant guide field, the MVA
414 minimum eigenvector provides the direction normal to the current sheet while putative
415 reconnection line orientations are given by the intermediate eigenvector direction [see, e.g.,
416 *Phan et al.*, 2006; *Gosling et al.*, 2007]. Table 2 summarizes the results for the
417 reconnection line orientations obtained at each spacecraft, together with the local magnetic
418 shear and Walén tests results for the exhausts. Figure 8 shows the orientation of the
419 reconnection lines at the three spacecraft. The main feature is that the reconnection lines at
420 all spacecraft have a significant tilt both away from the equator and away from the radial
421 direction to Sun.

422

423 **4.4 Signature of large-scale topological changes in suprathermal electrons**

424 Finally, we examine the large-scale topological changes that may be expected from the
425 process of magnetic erosion envisaged here (Figure 1). For this purpose we may use
426 suprathermal electrons as tracers (cf. introduction).

427 The suprathermal electron PADs displayed in Figure 3 show that this MC is
428 characterised by both closed and open field lines, as indicated by the presence of both bi-
429 and unidirectional suprathermal electrons. The unidirectional beams are observed anti-
430 parallel to the magnetic field at all spacecraft, consistent with the spacecraft observing the
431 same MC. The open field lines with unidirectional electrons observed in the core of the
432 MC, before the back region inferred previously, can be associated with the occurrence of
433 interchange reconnection at the Sun as has often been reported [e.g. *Crooker et al.*, 2004;
434 *Owens and Crooker*, 2006; *Lavraud et al.*, 2011]. Note, however, that such interchange
435 reconnection cannot affect the magnetic structure of the MC observed at 1 AU because
436 information (travelling at the Alfvén speed) does not have enough time to be transmitted to
437 1 AU.

438 The back regions of the MC were estimated to span from 9:53 to 11:43 UT (on 20

439 November) at ACE and from 23:40 to 03:20 UT (on 20-21 Nov.) at ST-A (vertical red lines
440 in Figure 3). Figure 9 shows 5-minute averages of the suprathermal electron pitch angle
441 distributions (PADs) at times just before and just after this expected transition between the
442 core of the MC and the back region for each spacecraft. The time intervals are respectively
443 9:00-9:05 UT and 10:30-10:35 on 20 Nov. (23:00-23:05 on 20 Nov. and 00:00-00:05 on 21
444 Nov.) for ACE (ST-A). Clear changes in both phase space density (PSD) values (parallel
445 and anti-parallel) and distribution angular widths are observed upon entry into the back
446 region for both ACE and ST-A. These are suggestive of a different strahl source for the
447 back region of the MC, as discussed next in section 5.4. Changes are also observed near the
448 end of the MC at ST-B, but these are not analysed, nor interpreted, since the azimuthal flux
449 balance analysis is deemed to be biased at this spacecraft, as discussed in section 5.4.

450 5. Discussion

451 We here discuss how this combined set of signatures provides significant, additional
452 evidence for the occurrence of magnetic erosion during the propagation of the MC
453 observed on November 19-21, 2007.

454 5.1. Evidence from multi-point magnetic flux imbalance analyses

455 The accumulated azimuthal magnetic flux analysis reveals the presence of an excess
456 magnetic flux in the trailing part of the MC at both ACE and ST-A. *Dasso et al.* [2006]
457 devised and used this method with single satellite observations, and without detailed error
458 assessment. In the present study, the MC is observed at 3 different and widely separated
459 spacecraft. This puts constraints on the spatial configuration of the MC. For instance, as
460 shown in *Owens et al.* [2012], passage through the leg of a MC significantly alters the
461 observed magnetic field signatures (e. g. ‘double flux rope’ signature). Such large
462 alterations of the magnetic field are not seen at ST-A. ST-A is therefore not sampling the
463 leg of the MC. The longer duration of the MC at ST-A may rather reflect a larger
464 expansion of the MC. This is compatible with the observed lower magnetic field strength,
465 the smaller difference between the MC velocity and solar wind ahead of it, and the absence
466 of a shock at ST-A.

467 The two MC axes obtained for ACE and ST-A are somewhat different (Figure 5), with
468 the latitude of the axis being larger at ST-A. Focusing on the parametric study for ACE in
469 Figure 5, it is very unlikely that the axis orientation at this spacecraft could be wrong by
470 more than 10°, and specifically towards lower latitude, since this would increase the
471 difference with the orientation found at ST-A and since errors on axis orientation are
472 particularly low at this spacecraft. All these results give strong confidence in the finding
473 that the azimuthal magnetic flux is strongly imbalanced at least at ACE, but also at ST-A.
474 The azimuthal magnetic flux contained in the back region is equivalent to the magnetic flux
475 that has been eroded at the front of the MC. According to our calculations, the amount of
476 azimuthal magnetic flux that was eroded from the front of the MC at ACE corresponds to
477 44% of the total, initial azimuthal magnetic flux measured, i.e., before erosion. This
478 calculation yields 49% at ST-A. Note that *Dasso et al.* [2006, 2007] estimated the amount
479 of eroded azimuthal magnetic flux with the same method for two MCs on 18-20 November
480 1995 and 9-11 November 2004: the values were respectively 57% and 17%.

481 We also noted that the trailing edge of the MC is compressed by a high-speed solar
482 wind. This compression is significant, as observed in the magnetic field (Figure 3), and as
483 shown by *Rouillard et al.* [2010] and *Farrugia et al.* [2011] for this MC. Although such
484 MC distortion may impact the MVA and FRF analyses, as mentioned in section 4 the
485 results are similar when the compressed back region is left out of the analyses at both ACE
486 and ST-A. This effect is also not expected to influence the accumulated flux calculation

487 since magnetic flux is conserved through mere adiabatic compression. Future studies ought,
488 nevertheless, to study uncompressed MCs.

489 5.2 Evidence from the estimated MC twist after erosion

490 The force-free fitting method allows us to estimate the MC α parameter. In the force
491 free model, $\alpha=2.41$ corresponds to a completely poloidal field at the outer MC boundaries
492 ($r = 1$). We obtain for ACE a value of 2.16 when analyzing the full MC interval (Table 1).
493 We obtain a value of 1.92 when the back region is left out of the analysis, i.e., when
494 analysing the symmetric part of the MC only. We may claim that this is consistent with an
495 eroded MC in the force-free model assumption. However, because we have no knowledge
496 of the initial configuration (in terms of α parameter) of the MC at the time of its initiation at
497 the Sun, this result only provides an additional element but may not be viewed as a strong
498 argument.

499 5.3 Evidence from the observation of reconnection at the MC front boundary

500 MC erosion during propagation in the interplanetary medium implies the occurrence of
501 magnetic reconnection at its front boundary, as depicted in Figure 1. As was demonstrated
502 in section 4.3, signatures of reconnection exhausts at the front boundary of the MC were
503 observed at all spacecraft (though with variable uncertainties owing to different time
504 resolutions and exhaust widths). This demonstrates that the expected magnetic
505 reconnection did occur, at least at the position and time of observation, for this particular
506 MC. We note, however, that although magnetic reconnection at the front boundary of the
507 MC is a prerequisite to the erosion mechanism invoked here, it needs not be observed
508 specifically at the spacecraft at the time of observation as long as it did occur at earlier
509 times during propagation. Interestingly, the erosion is observed here for a rather slow MC
510 (~ 450 km/s). Erosion is, however, expected to be stronger for faster MCs owing to
511 increased compression at the forward shock, with associated increased reconnection rates.

512 Figure 10 shows the reconnection lines orientations at the MC fronts, deduced from
513 MVA analysis, in the $Y-Z_{\text{HEE}}$ plane. The reconnection lines have somewhat different tilt
514 angles at each spacecraft, which is not unexpected owing to the large inter-spacecraft
515 distances and the 3D geometry of a MC that interacts with its environment. Although it is
516 not the purpose of the present study, we note that the reconnection line tilts in the $Y-Z$
517 plane are large. This brings up the question of whether there is a single or several patchy
518 reconnection lines present along the front of the MC. This is in analogy to the issue of
519 extended versus patchy reconnection at Earth's dayside magnetopause as a function of IMF
520 conditions, and which also depends on complex 3-dimensional geometrical considerations
521 (as further discussed in section 5.5) and on the influence of various processes occurring at
522 the shock and in the sheath.

523 5.4 Evidence for a different suprathermal electron strahl source

524 The suprathermal electrons PADs in the MC back regions show clear changes at ACE
525 and ST-A as compared to the core of the MC. Because the erosion process implies large-
526 scale topological changes (Figure 1), we do expect the source of the strahl in the back
527 region to be different from that in the MC core. This is what is observed for both ACE and
528 ST-A at the expected times (within ± 1 hours). An unexpected signature would be to
529 observe no changes at all in the PADs as the spacecraft enter the inferred back regions.

530 The observed enhanced magnetic field in the back region and the presence of a trailing
531 high-speed stream (cf. Figure 3) suggest adiabatic compression is occurring. From
532 Liouville's theorem, such an adiabatic compression would result in a larger PAD width of
533 the strahl, but without any increase in absolute phase space density values around 180° .
534 This is opposite to what is observed at the transition between the core of the MC and the
535 inferred back regions, where the phase space density at 180° significantly increases
536 (decreases) at ST-A (ACE) while the PAD width does not change or even decreases at both

537 spacecraft. The strahl source is thus different in the back regions at both ACE and ST-A.

538 5.5 Reconnection scenarios and complexity of the 3D global topology

539 These signatures in the suprathermal electron PADs are thus consistent with a
540 topological change at the front of the MC and subsequent erosion. However, because of the
541 complex topology of the MC and of the possibly patchy reconnection lines, we have no
542 obvious way of knowing where the eroded magnetic field may now connect to in the
543 heliosphere, and whether or not they should be singly or doubly connected to the Sun.
544 Figure 11 illustrates this fact. Figures 11a-b and 11c-d respectively show configurations
545 where reconnection lines with the rough local properties observed at ST-A and ACE are
546 used. Because the magnetic field and suprathermal electron properties at the MC front
547 boundaries are different at ACE and ST-A, as well as in the slow solar wind ahead of it
548 with different sectors being observed at ACE and ST-A (i.e., the strahl is measured at 0° at
549 22UT on 19 Nov. at ACE and at 180° at 19UT on 19 Nov. at ST-A), the obtained new
550 connectivity inside the MC may have either closed or open magnetic topologies at other
551 locations along the magnetic fields of the MC.

552 These configurations, however, are over-simplified. Placing both reconnection
553 scenarios into the same picture significantly alters these simple geometries and makes the
554 global 3D topology more complex. This is illustrated in Figure 11e-f where all cases of
555 parallel, anti-parallel or bidirectional suprathermal electrons may be found at various places
556 in the MC depending on where reconnection occurs. Figures 11e-f may not be viewed as
557 realistic either. This is because even more complex configurations can be envisaged if
558 reconnection varies spatially and temporally, and if reconnection occurs along extended
559 lines rather than points as depicted in the figures for sake of simplicity. Adding to this
560 complexity is the fact that part of the MC is likely disconnected from the Sun at one end
561 (left-hand side of MC in all figures) through interchange reconnection in the corona.

562 In conclusion, we may not attempt to fully explain the characteristics of suprathermal
563 electrons in the MC but simply note that suprathermal electron PADs must change in the
564 back region. We may not know what strahl and PAD properties are to be expected with the
565 new connectivity because we do not know the global 3D topology that follows from such
566 reconnections. This is also why the relative changes in PAD profiles, as observed in Figure
567 9 (red and blue curves), do not have to be the same at all spacecraft (again, owing to a
568 complex 3D geometry). PAD properties (e.g., at ST-B) may thus not be used alone to study
569 erosion. Future studies ought to investigate this further, for instance through the use of
570 global modelling.

571 5.6 Inferences for the preferential location and rate of magnetic reconnection during 572 propagation

573 We note that *Gosling and Szabo* [2008] found a reconnection exhaust at the trailing
574 boundary of the MC (11:46 UT at WIND / 11:42 UT at ACE on 20 November). This likely
575 stems from the compression that occurs as the trailing high-speed stream overtakes the MC.
576 Because this compression is expected to build-up gradually as it propagates in the
577 heliosphere, it is probable that the reconnection process at the trailing boundary has not
578 been much efficient in the inner heliosphere. By contrast, since the Alfvén speed in the
579 solar wind increases as one approaches the Sun [*Fujimoto et al.*, 2007; *Lavraud and*
580 *Borovsky*, 2008], and magnetic reconnection rate scales with the Alfvén speed, we may
581 expect that a significant portion of the magnetic erosion investigated here has in fact
582 occurred in the inner parts of the heliosphere.

583 From the observed azimuthal magnetic flux erosion and knowledge of the transit time
584 from the Sun, we can estimate the average reconnection rate which prevailed at the front
585 MC boundary during propagation. *Howard and Tappin* [2009] observed this CME from
586 different viewpoints on 15 November at 18:10 UT (by COR2-B), 18:40 UT (by COR2-A)

587 and 18:50 UT (by LASCO2). We choose the mean value of 18:30 UT. The transit time to
588 ACE (ST-A) is then in the range 99h 54 min to 113h 12min (99h 30min to 128h 50min)
589 using the front and rear boundaries of the MC. We use both times to estimate uncertainties
590 on the average reconnection rate because erosion is likely ongoing during the spacecraft
591 sampling of the MC. This simple calculation yields average reconnection rates of 0.12-0.14
592 mV/m at ACE and 0.19-0.22 mV/m at ST-A. Using the results of Dasso et al. [2006,2007],
593 the average reconnection rates for the 18-20 October 1995 and 9-11 November 2004 MC
594 events are estimated to be 0.51 and 0.45 mV/m; these are of the same order of magnitude,
595 though somewhat higher. On average, these estimations are larger than those given in case
596 studies of reconnection exhausts at L1 by *Davis et al.* [2006], *Phan et al.* [2006], and *Wang*
597 *et al.* [2010] (0.02, 0.03 and 0.05-0.08 mV/m respectively), but as explained above this
598 may be expected since reconnection rates ought to be larger closer to the Sun.

599 6. Conclusion

600 The present work provided a significant advancement in confirming the occurrence
601 of MC erosion during their propagation from the Sun to the Earth, thanks to a detailed
602 analysis of several key signatures expected to result from this process. The opportunity to
603 observe this phenomenon from several distant vantage points with STEREO and L1 data
604 constituted a significant asset to infer the global geometry of the MC, which was shown to
605 be compatible with a unique large-scale flux-rope at three distant spacecraft in the
606 heliosphere. The inferred erosion mechanism has significant potential implications for
607 space weather since it may lead to the removal of part of the southward oriented magnetic
608 field that impinges on Earth for some MCs. Future works also ought to quantify this
609 possibility for all MCs of solar cycle 23.

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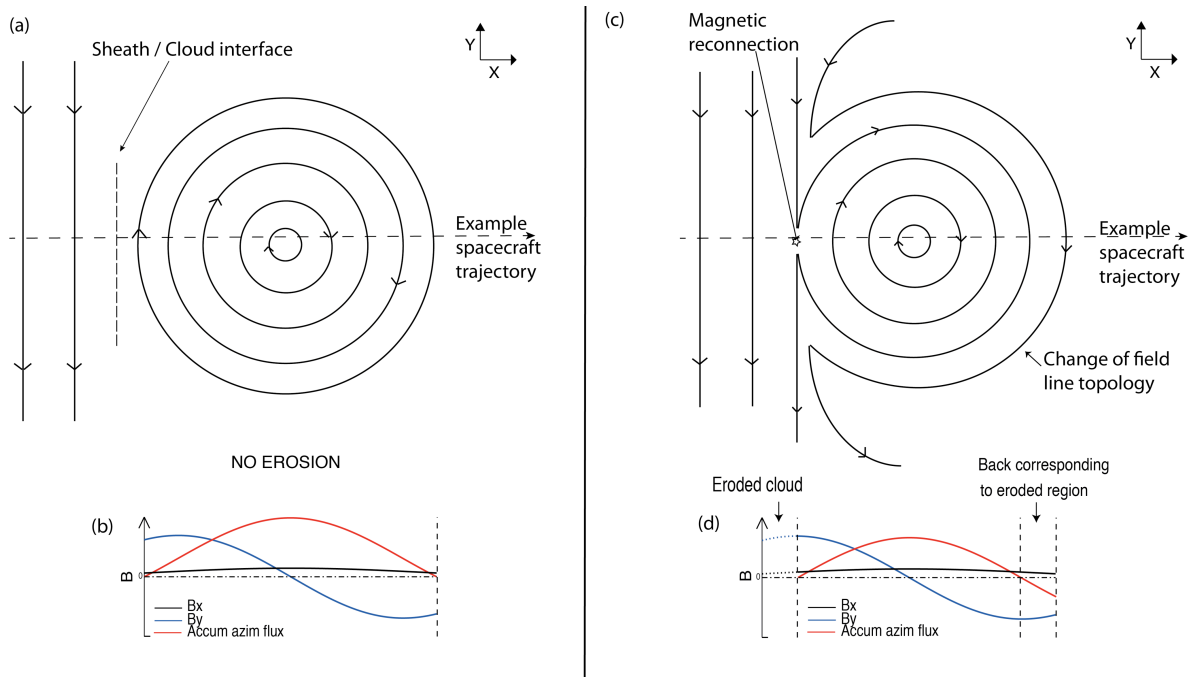
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RUFFENACH ET AL.: MAGNETIC CLOUD EROSION BY MAGNETIC RECONNECTION

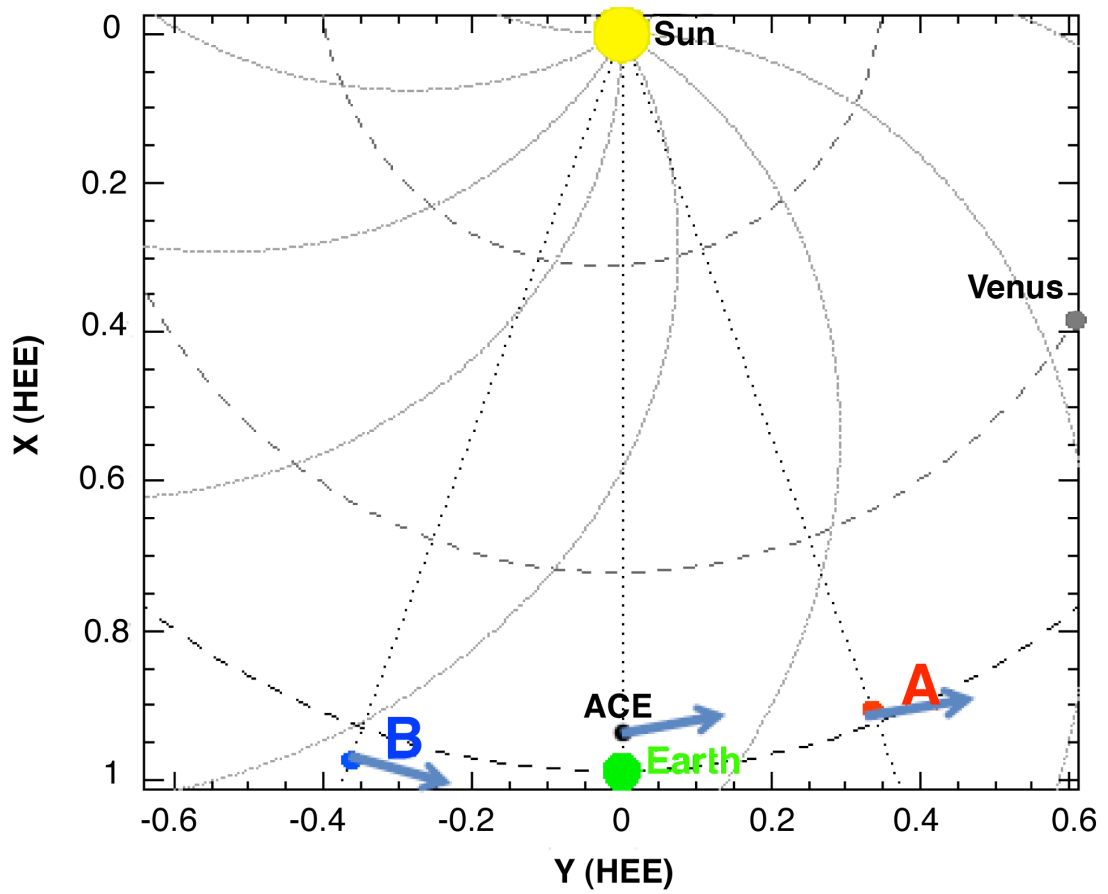
FIGURE CAPTIONS:



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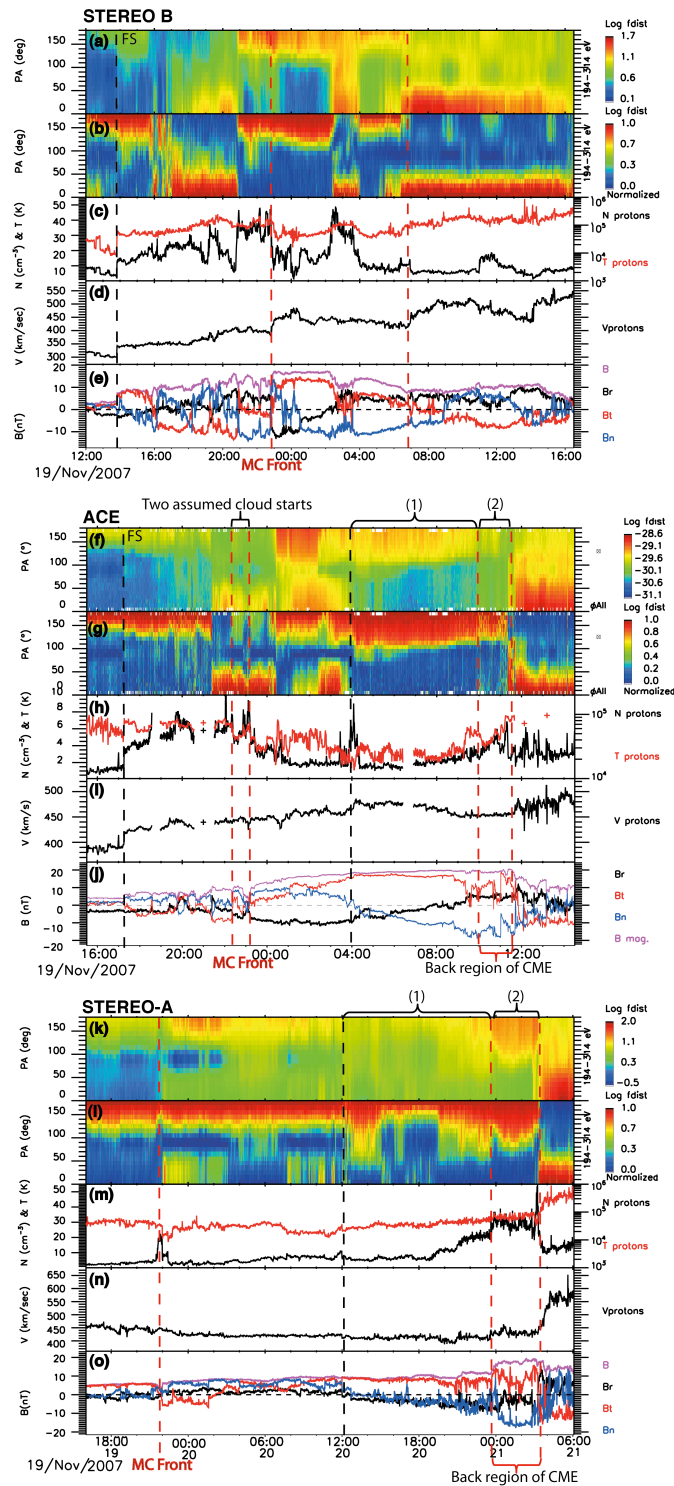
Figure 1. Schematic representing the magnetic structure of non-eroded (a) and eroded (c) MCs together with the expected variations in the magnetic field components and accumulated azimuthal flux (b and d). The analysis needs to be made in the proper MC coordinate system as is implicit here.

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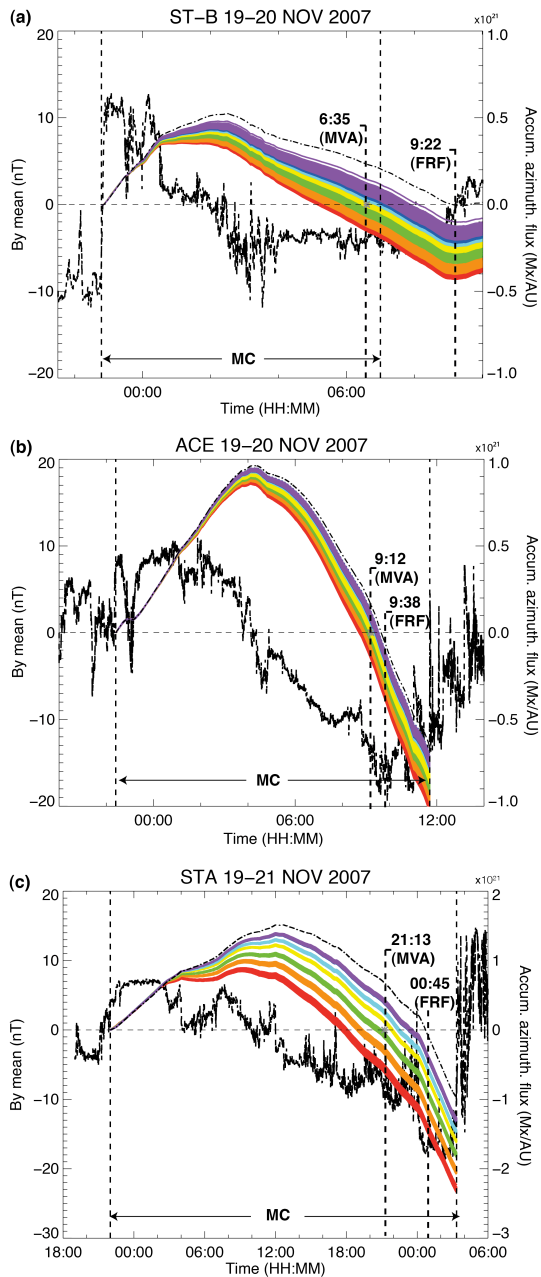
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Figure 2. ACE, ST-A, ST-B, and Earth locations on November 19-20, 2007 in the ecliptic plane with the respective projection of MC axis orientations inferred from MVA analysis.



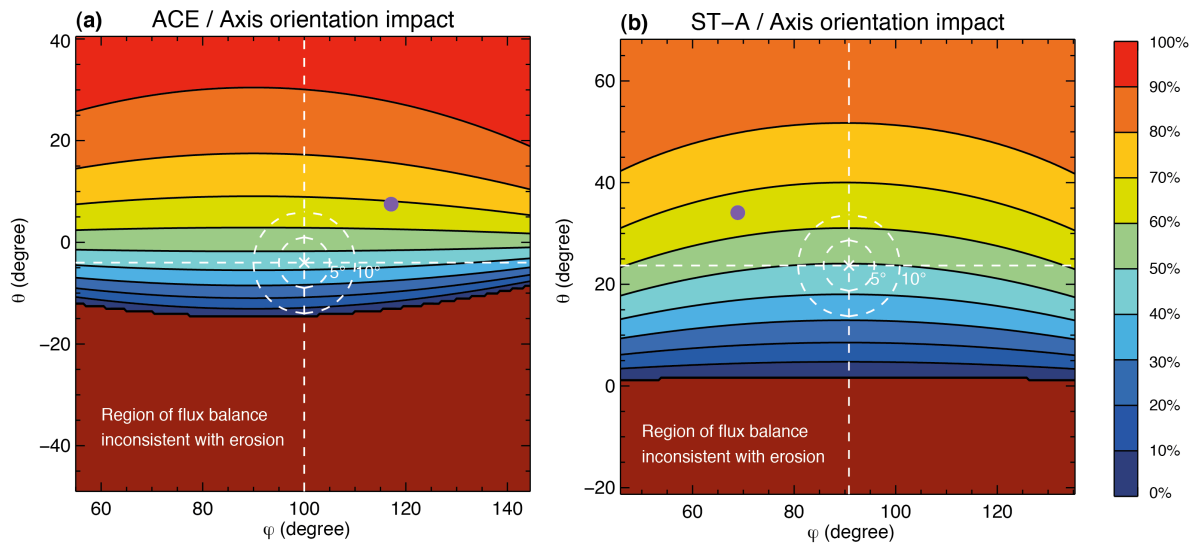
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Figure 3. Plasma and magnetic field data from ST-B, ACE, and ST-A during the period 19-21 November 2007. The various MC boundaries used are marked with red dashed lines (see text for details). The panels (a/f/k) show the suprathermal electron pitch angle distributions, (b/g/l) the normalized (between 0 and 1 for each time sample) pitch angle distributions, (c/h/m) the proton temperature (red line) and proton density (black line), (d/i/n) the proton speed, and (e/j/o) the magnetic field components in RTN coordinates. Region (1) corresponds to the open MC region interpreted as resulting from interchange reconnection at the Sun. Region (2) is deemed to be the back region resulting from erosion. It also shows unidirectional electrons but with markedly different strahl properties (cf. Figure 9). Forward shocks (FS) are shown with a dashed line at ACE and ST-B.



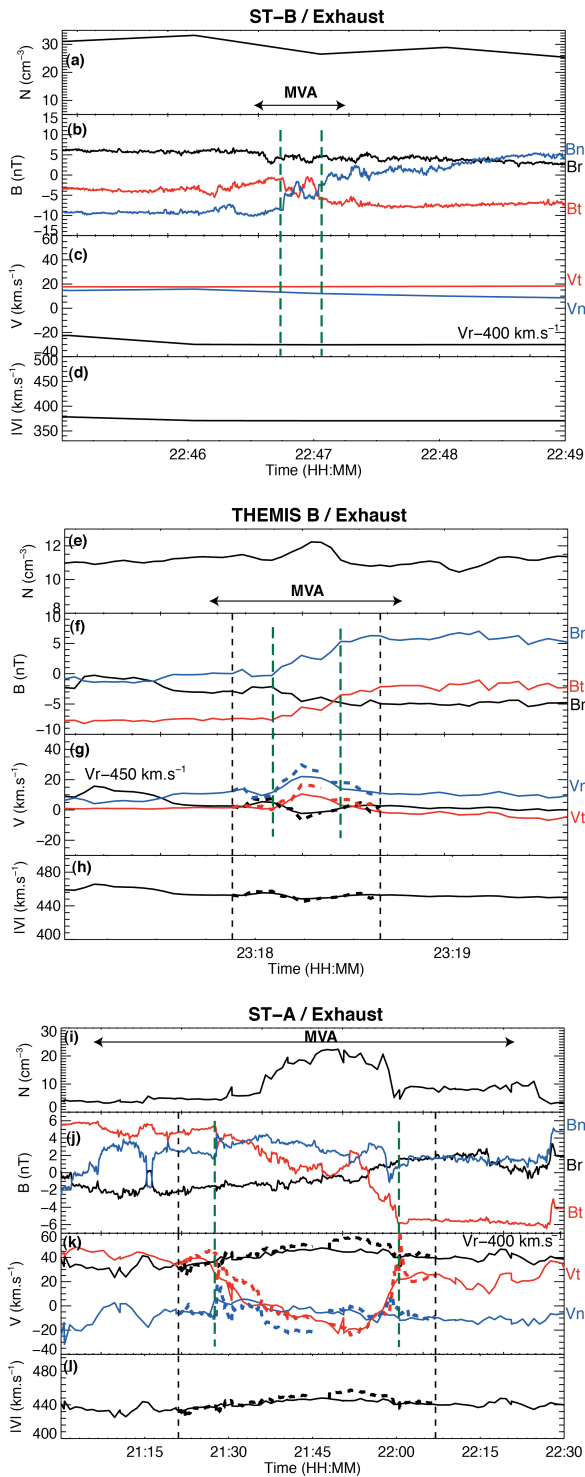
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Figure 4. $B_{y\text{cloud}}$ component and accumulated azimuthal magnetic flux per unit length for ST-B (a), ACE (b), and ST-A (c). The colored curves show the results using orientations deduced from MVA with bootstrap method applied to different intervals (cf. Section 4.1.2). The dash-dotted curves show the results using the orientation deduced from force-free MC fitting. Vertical lines indicate the boundaries of the MC and the time at which the azimuthal flux is balanced (cuts zero) for both the (mean of) MVA and FRF methods. Cf. also Table 1 for details.



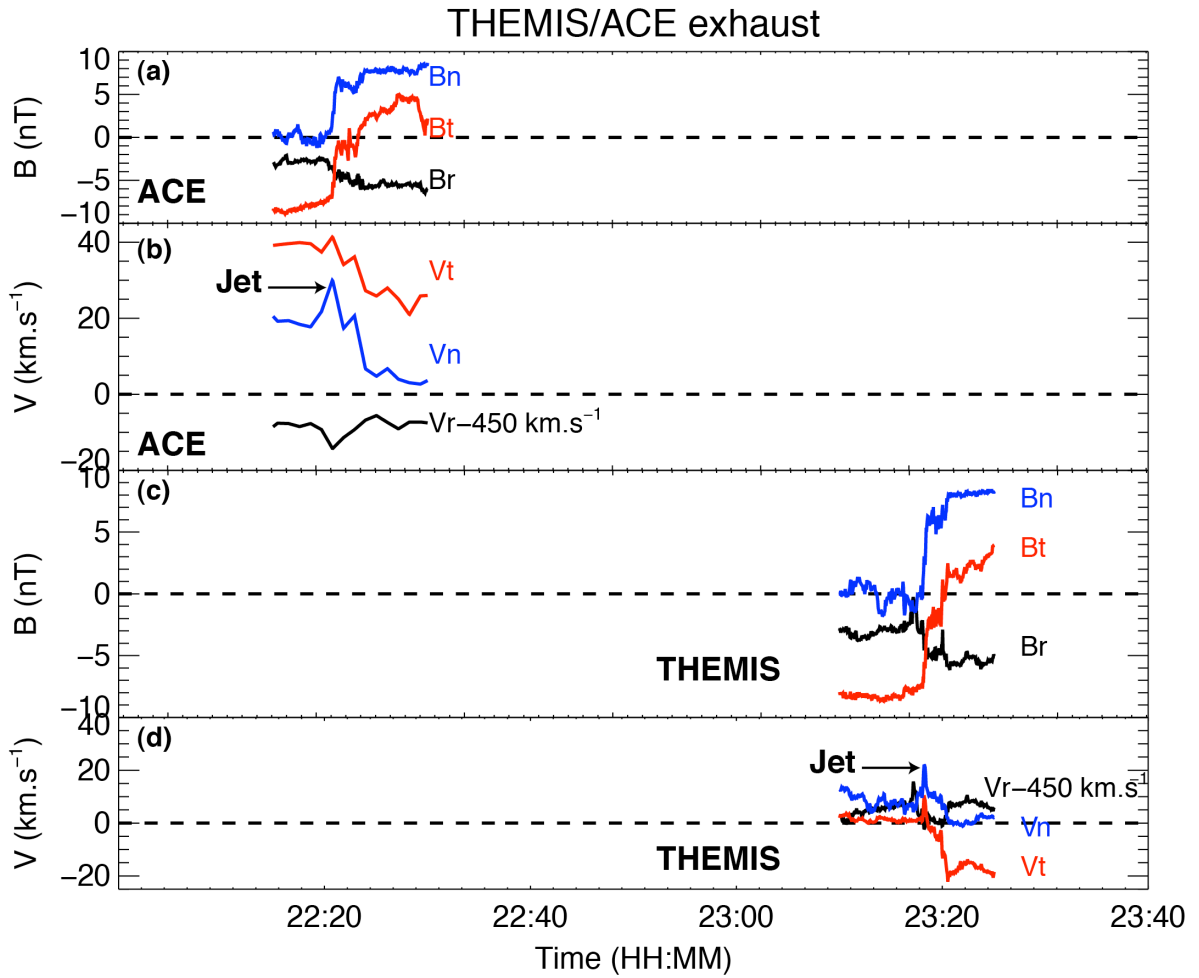
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Figure 5. Parametric study of the impact of an arbitrary MC axis orientation on the amount of azimuthal magnetic flux eroded from the front of the MC at ACE (a) and ST-A (b), as defined in Section 4.1.4. The display is centered on the orientation given by the mean MC axis orientation from our analyses (Cf. Table 1). The line separating the dark blue and the brown regions in the plots corresponds to axes orientations for which the azimuthal flux is exactly balanced (in the front and back parts of the MC). Regions with other colors (blue to red) are consistent with erosion of various degrees (cf. color scale for MC flux erosion percentage), while the entire brown part of the plot is inconsistent with erosion and the presence of a back region. The axis orientation obtained by *Farrugia et al.* [2011] using MVA (from WIND and ST-A) is given as a solid purple circle for context.



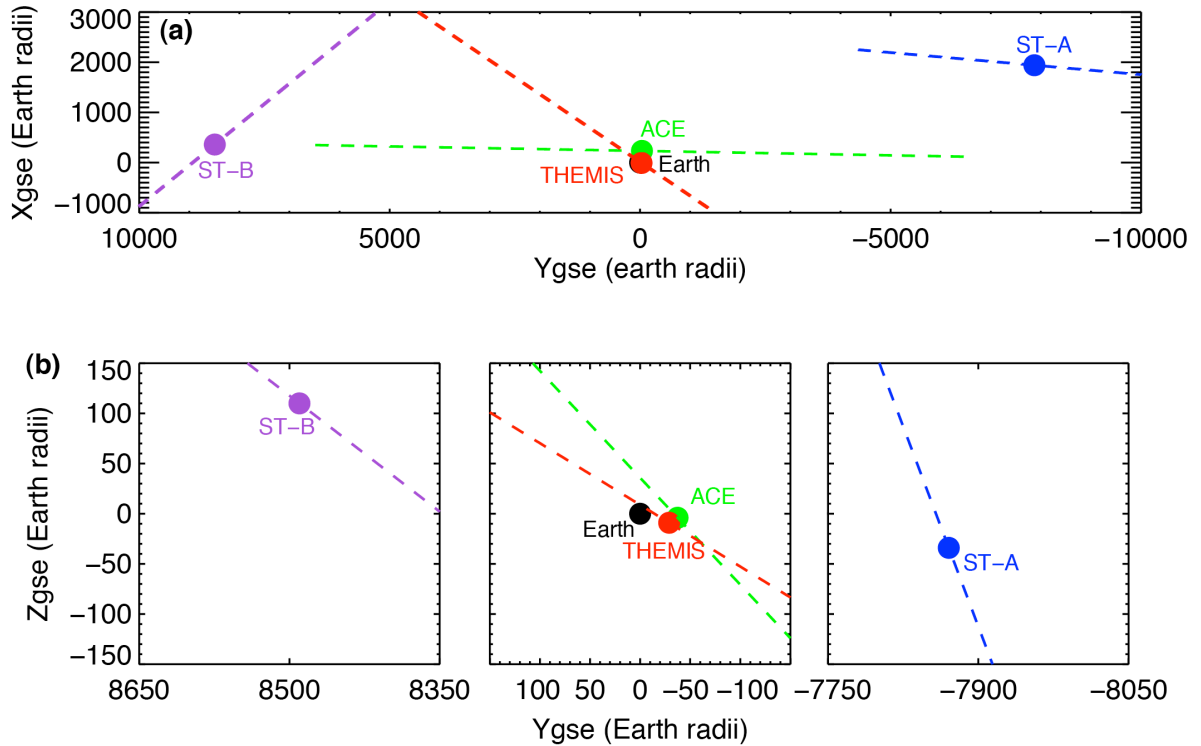
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Figure 6. Data for the exhausts seen at ST-B, THEMIS-B and ST-A at the front of the MC together with Walén test results when the time resolution is sufficient (THEMIS-B and ST-A). For each spacecraft the panels show: (a/e/i) Proton density, (b/f/j) magnetic field components, (c/g/k) proton velocity components observed and predicted (dashed lines), and (d/h/j) proton velocity magnitude observed and predicted (dashed lines). The two black vertical lines denote the reference times for the Walén test (which is performed “inward”). The green vertical lines denote the edges of the exhaust, i.e., the bifurcated current sheets. The time interval used to determine the orientation of the reconnection line through MVA is also indicated with an arrow (Cf. Table 2).



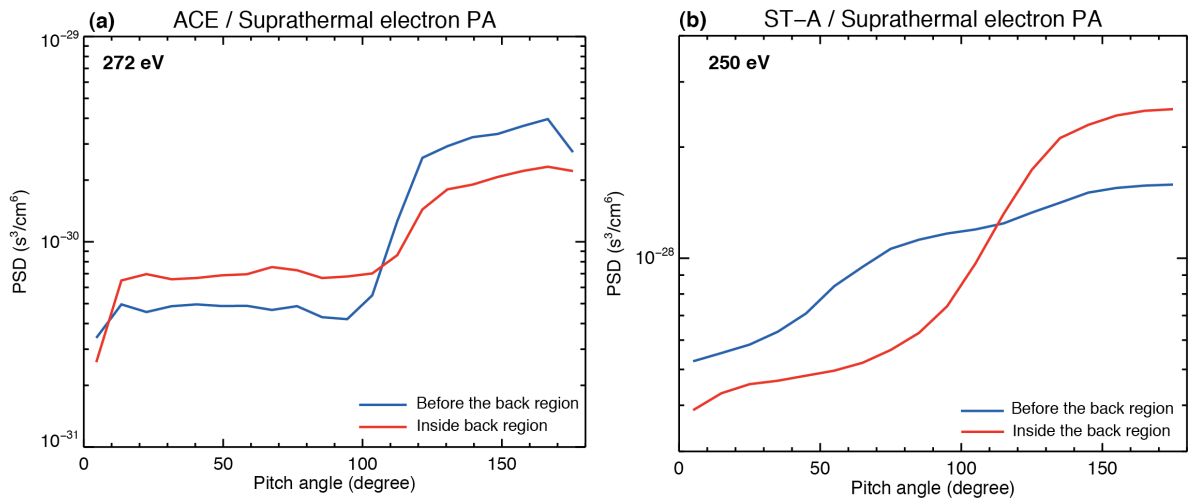
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Figure 7. Data for the exhaust seen at ACE and THEMIS-B at the MC front boundary on 19 November. Panels (a) and (c) show the magnetic field components for ACE and THEMIS, respectively. Panels (b) and (d) show the associated velocity components. Despite a resolution too low to allow a proper Walén test, a proton jet is clearly also observed at ACE at the front boundary of the MC.



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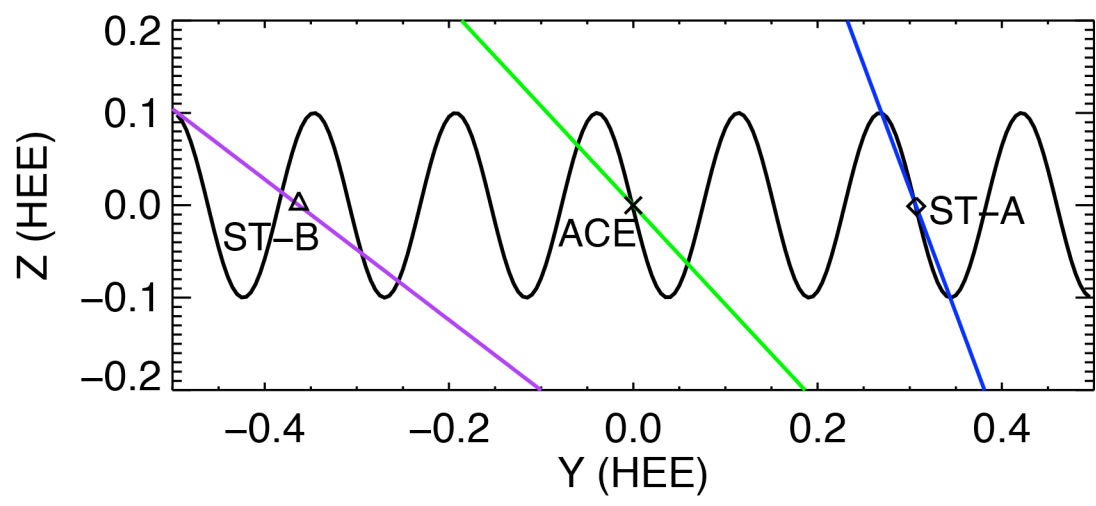
Figure 8. Projections of the reconnection line orientations at each spacecraft in GSE coordinates at 22:00 UT on 19 November 2007 in the X-Y_{GSE} (a) and Z-Y_{GSE} (b) planes.



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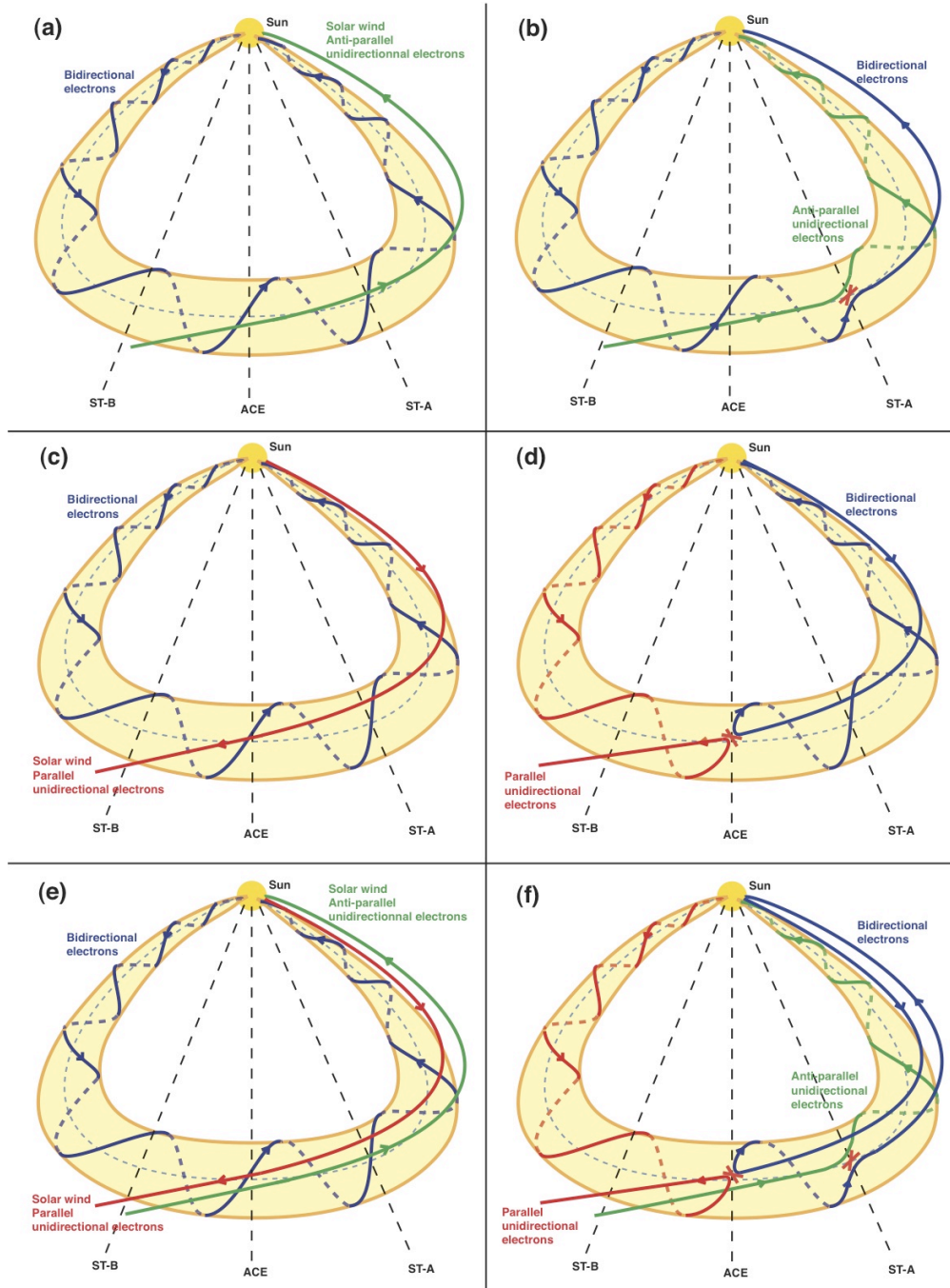
Figure 9. ACE (a) and ST-A (b) suprathermal electron pitch angle distributions obtained in the MC back region (red curve) and the MC core (blue curve), at times close to the boundary separating those two regions (see section 4.4 for details). Each is an average of consecutive PAD samples over 5 minutes.

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Figure 10. Illustration of the projected helical MC field (black curve), with estimated reconnection line orientations (color curves), for the exhausts observed at the MC front boundaries at the three spacecraft in the ZY planes (HEE coordinates). This suggests that it may not be the same reconnection line observed at all spacecraft.



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Figure 11. Illustration of different reconnection scenarios at the front of the MC and resulting global three-dimensional topologies. Panels a, c and e depict the topology of the MC and solar wind magnetic field lines before magnetic reconnection occurs. Panels b, d and f represent the global magnetic field topology that may be inferred in the case when magnetic reconnection occurs at ST-A (b), ACE (d) and at both spacecraft (f). Reconnection is assumed with solar wind from a toward sector at ST-A and an away sector at ACE, as observed. Blue lines correspond to closed magnetic field lines where counter-streaming suprathermal electron beams may be expected. Green and red lines respectively correspond to open field lines with anti-parallel and parallel unidirectional suprathermal electrons. Arrows show the orientation of the magnetic field. These topologies, and inferred electron properties, must be viewed as highly idealized and thus not realistic. Much more complex, and thus unpredictable, configurations may be expected as a function of the type and spatio-temporal variability of reconnection lines at the MC front boundary.

1016 **TABLES:**

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	ACE	ST-A	ST-B
MVA and cloud-fitting time interval	23:13 (19 Nov.)- 11:42 (20 Nov.)	22:00 (19 Nov.)- 3:20 (21 Nov.)	22:52 (19 Nov.)- 7:00 (20 Nov.)
Azimuthal flux integration start time	22:22 (19 Nov.)	22:00 (19 Nov.)	22:47 (19 Nov.)
MC axis orientation from the mean of all MVA results (with standard deviations)	$\theta=-3^\circ\pm 1^\circ$ $\varphi=101.5^\circ\pm 0.4^\circ$	$\theta=31^\circ\pm 7^\circ$ $\varphi=84^\circ\pm 6^\circ$	$\theta=-39^\circ\pm 4^\circ$ $\varphi=96^\circ\pm 8^\circ$
MC axis orientation from FRF	$\theta=-5^\circ$ $\varphi=99^\circ$	$\theta=17^\circ$ $\varphi=97^\circ$	$\theta=-50^\circ$ $\varphi=92^\circ$
MC axis orientation: mean of results from MVA and FRF methods	$\theta=-4^\circ$ $\varphi=100^\circ$	$\theta=24^\circ$ $\varphi=91^\circ$	$\theta=-45^\circ$ $\varphi=94^\circ$
Start of back region inferred from electron PAD	9:53 (20 Nov.)	23:40 (20 Nov.)	/
Time of flux balance (mean of results from MVA and FRF methods)	9:26 \pm 13min (20 Nov.)	22:59 \pm 1:48 (20 Nov.)	7:58 \pm 1:23 (20 Nov.)
Intermediate/minimum eigenvalue ratio (mean from all MVA analyses)	11.3	6.31	6.32
Impact parameter from FRF (positive means spacecraft crosses north of MC center axis)	0.18	0.03	-0.11
Alpha parameter from FRF	2.16	2.39	1.94

Table 1. Summary of the results obtained for the azimuthal flux balance-related analyses at each spacecraft.

	ACE	THEMIS	ST-A	ST-B
Time interval of exhaust location	22:20:30-22:21:30	23:18:05-23:18:26	21:28 – 22:01	22:46:45-22:47:03
Time interval of MVA	22:19:30-22:22:30	23:17:44-23:18:47	21:13-22:16	22:46:36-22:47:12
Reconnection line orientation (GSE)	[-0.01, -0.68, -0.73]	[-0.49, -0.74, -0.45]	[-0.03, -0.35, -0.94]	[0.54, -0.67, -0.51]
Walén Test	Insufficient resolution	ok	ok	Insufficient resolution
Magnetic shear angle	72.5°	73.0°	142.8°	62°

1056 **Table 2.** Properties of the exhausts observed at the MC front boundaries at each spacecraft.