

<sup>1</sup> Cassini Plasma Observations of Saturn's  
<sup>2</sup> Magnetospheric Cusp

Jamie M. Jasinski,<sup>1,2,3</sup> Christopher S. Arridge,<sup>4</sup> Andrew J. Coates,<sup>1,3</sup>

Geraint H. Jones,<sup>1,3</sup> Nick Sergis,<sup>5</sup> Michelle F. Thomsen,<sup>6</sup>

Daniel B. Reisenfeld,<sup>7</sup> Norbert Krupp,<sup>8</sup> and J. Hunter Waite Jr.<sup>9</sup>

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<sup>1</sup>MSSL, UCL, London, UK.

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<sup>2</sup>CLaSP, University of Michigan, Ann Arbor, MI, USA.

<sup>3</sup>The Centre for Planetary Sciences at UCL/Birkbeck, London, UK.

<sup>4</sup>Dept. of Physics, Lancaster University, Lancaster, UK.

<sup>5</sup>Office for Space Research and Technology, Academy of Athens, Athens, Greece.

<sup>6</sup>Planetary Science Institute, Tucson, Arizona, USA.

<sup>7</sup>Dept. of Physics and Astronomy, University of Montana, Montana, USA

<sup>8</sup>Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany.

<sup>9</sup>Southwest Research Institute, San Antonio, Texas, USA.

### Key Points

- Evidence for lobe and dayside magnetic reconnection occurring at times near-simultaneously at Saturn.

- Plasma signatures show that magnetic reconnection can occur in a 'bursty' and 'quiescent' manner.

- Cusp observations occur for a variety of solar wind conditions.

### Abstract

The magnetospheric cusp is a funnel-shaped region where shocked solar wind plasma is able to enter the high latitude magnetosphere via the process of magnetic reconnection.

The plasma observations include various cusp signatures such as ion energy dispersions as well as diamagnetic effects. We present an overview analysis of the cusp plasma observations at the Saturnian magnetosphere from the Cassini spacecraft era. A comparison

of the observations is made as well as classification into groups due to varying characteristics. The locations of the reconnection site are calculated and shown to vary along

the subsolar magnetopause. We show the first in situ evidence for lobe reconnection that occurred at nearly the same time as dayside reconnection for one of the cusp crossings.

Evidence for 'bursty' and more 'continuous' reconnection signatures are observed in different cusp events. The events are compared to solar wind propagation models and it

is shown that magnetic reconnection and plasma injection into the cusp can occur for a variety of upstream conditions. These are important results because they show that

Saturn's magnetospheric interaction with the solar wind and the resulting cusp signatures are dynamic, and that plasma injection in the cusp occurs due to a variety of solar wind

25 conditions. Furthermore, reconnection can proceed at a variety of locations along the  
26 magnetopause.

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## 1. Introduction

27 *Chapman and Ferraro* [1931a, b] were the first to postulate the idea of the magne-  
28 spheric cusp, showing that within the magnetosphere there would be a pair of magnetic  
29 'null' points, one in the northern hemisphere, and one in the southern. This magnetic  
30 funnel-shaped region of the cusp is always present due to the geometry of the field lines  
31 in an open magnetosphere. However the direct entry of solar wind plasma into this re-  
32 gion occurs via the process of magnetic reconnection between the interplanetary magnetic  
33 field (IMF) and closed magnetospheric field lines at the subsolar point, as well as the  
34 subsequent poleward convection of the open field-line which is now known to be part of  
35 the Dungey Cycle [*Dungey*, 1961]. Consequently, the observation of open cusp field lines  
36 is usually identified through (injected solar wind) plasma in the high latitude dayside  
37 magnetosphere from the reconnection site [e.g. *Frank*, 1971; *Russell et al.*, 1971; *Gosling*  
38 *et al.*, 1990]. Reconnection can also occur in the lobe region between the IMF and open  
39 magnetospheric field lines, which results in the newly reconnected field line convecting  
40 equatorward. Therefore, the cusps are important to study as they are a source of direct  
41 entry of matter, energy and momentum into a magnetosphere. They are also well situated  
42 in space so as to observe and study the effects of reconnection, as the cusps map to a wide  
43 range of locations at the magnetopause. Much of the research which has been carried out  
44 on the topic of the cusp has been done for Earth (e.g. *Smith and Lockwood* [1996] and  
45 *Cargill et al.* [2005]).

46 The observations in the cusp are of magnetosheath plasma; ions with low energies of  
47 a few hundred eV up to  $\sim 1$  keV at Earth [e.g. *Heikkila and Winningham*, 1971; *Pitout*

48 *et al.*, 2009]. The most characteristic cusp signature is that of the ion plasma displaying  
49 an energy-latitude (energy-time) dispersion. The particles that are injected have different  
50 energies (and therefore differing field-aligned velocities). This means that particles with  
51 two different energies will have a different time-of-flight along a field line. As a result, the  
52 particle with the higher energy will travel faster along the field line. Whilst the particles  
53 travel along the magnetic field, the flux tube is convecting poleward, causing the higher  
54 energy particle to reach any point along the field line at a lower latitude than a lower  
55 energy particle. This results in lower energy particles reaching higher latitudes later (in  
56 time) along the field line than the higher energy particles. Therefore the particles become  
57 dispersed in latitude. This gives rise to the ‘velocity filter effect’ [*Shelley et al.*, 1976; *Hill*  
58 *and Reiff*, 1977; *Reiff et al.*, 1977; *Lockwood et al.*, 1994] that is observed by a particle  
59 detector. A spacecraft that is moving through the cusp will observe an energy-latitude  
60 dispersion in the ions, whereby the higher energy ions are observed at lower latitudes (as  
61 well as earlier in time) for a particular injection point.

62 After reconnection happens, the solar wind enters the magnetosphere along the open  
63 field line at the magnetopause. A spacecraft will observe plasma that has been injected  
64 from different areas along the magnetopause after reconnection. However, the lowest  
65 energy observed will be from the plasma that was injected first (at the reconnection site).  
66 Therefore, the low-energy ion cutoff represents the plasma injected from the reconnection  
67 site, and the higher energies simultaneously observed will be due to ions injected later  
68 in time that have “caught up” with the ion with the lowest energy. This is why the ion  
69 dispersions are marked by the lowest-energy ion cutoff.

70 Subsolar magnetopause reconnection occurs most favourably when the magnetosheath  
71 magnetic field is anti-parallel to the magnetospheric field [*Burton et al.*, 1975; *Mozer and*  
72 *Retinò*, 2007]. At Saturn, subsolar magnetopause reconnection is therefore favoured for  
73 northward IMF, while southward IMF favours a location anti-sunward of the cusp in  
74 the lobes, either in one hemisphere or in both [e.g. *Gosling et al.*, 1991; *Øieroset et al.*,  
75 1997]. Due to magnetic tension forces, the reconnected magnetic field line at the lobes  
76 convects equatorward and so the ion energy-latitude dispersion observed is opposite to  
77 that discussed previously, with the higher energy ions now observed at higher latitudes.  
78 This is called a ‘reverse-sense’ dispersion (as opposed to a ‘normal-sense’ dispersion for  
79 subsolar reconnection). Knowing the direction of the spacecraft trajectory and the sense  
80 of the dispersion reveals the general location of the reconnection site.

81 The second type of dispersion observed in the cusp are ion energy-pitch angle disper-  
82 sions [*Burch et al.*, 1982]. Ions that have a more anti-planetward pitch angle will be  
83 observed to have higher energies, than ions possessing more planetward pitch angles. The  
84 ions observed in the cusp with anti-planetward pitch-angles have already mirrored at low  
85 altitudes, and therefore travelled a larger field-aligned distance from the reconnection site,  
86 compared to ions with a planetward pitch-angle which have not yet mirrored. In order  
87 for this to occur, the ions with an anti-planetward pitch-angle must have a higher energy  
88 so that their parallel velocity is larger, allowing them to be observed simultaneously.

89 The final common cusp signature is that of diamagnetic depressions in the observed  
90 magnetic field. Analysis of the diamagnetic depressions and the physics of these depres-  
91 sions are the focus of a future paper and are not discussed further here, however we do  
92 use the depressions to aid detection of the cusp in this paper.

93 The Earth's cusp has been observed to move equatorward during times when the IMF  
94 of the solar wind turns to a southward direction [e.g. *Burch*, 1973]. This is due to an  
95 increase in reconnection rate when the shear between the IMF and geomagnetic field lines  
96 increases so the geomagnetic field is eroded at the dayside and the open-closed field line  
97 boundary subsequently moves equatorward. The cusp is observed to move azimuthally  
98 depending on the IMF conditions [e.g. *Burch et al.*, 1985; *Candidi et al.*, 1989]. With a  
99 large  $B_y$  component in the IMF, the newly opened field lines will have a dawnward and  
100 duskward flow for the northern and southern hemispheres respectively when  $B_y > 0$ . The  
101 opposite is true for an IMF  $B_y < 0$ . The corresponding ionospheric flows also behave  
102 in a similar fashion. This is due to the convection and magnetic tension force acting  
103 in an azimuthal direction after reconnection instead of a completely poleward direction  
104 when the IMF is completely antiparallel to the dayside magnetospheric field interior to  
105 the magnetopause.

106 *Pitout et al.* [2006, 2009] undertook very large statistical investigations involving terres-  
107 trial cusp observations made by the Cluster mission. They found that the location of the  
108 cusp depends on the dynamic pressure of the solar wind as well as its IMF- $B_y$  component  
109 (as discussed previously). A seasonal effect was seen where the cusp is wider when the  
110 cusp 'faces' the solar wind more directly. The northern and southern hemisphere cusp  
111 observations are centred on 12:00 local time (LT) with a range of 10:00–14:00 LT and  
112 between 75–80° invariant latitude. The northern cusp is more commonly located in the  
113 morning sector for negative  $B_y$  and in the afternoon for positive  $B_y$ , with an opposite  
114 trend observed in the south.



115 The first confirmation of a cusp observation at Saturn occurred in the northern hemi-  
116 sphere [*Jasinski et al.*, 2014]. The authors reported multiple ion energy-latitude disper-  
117 sions with a ‘stepped’ structure, which have been shown to be due to ‘bursts’ or ‘pulses’  
118 of reconnection occurring at the magnetopause [e.g. *Lockwood and Smith*, 1994; *Lockwood*  
119 *et al.*, 2000]. Analysis of the energy-pitch angle dispersions showed that the reconnection  
120 site at the Saturnian magnetopause was changing location during the observations. Two  
121 cusp observations in the southern hemisphere were reported by *Arridge et al.* [2016]. The  
122 authors also found that the southern cusp oscillates with the oscillation of the auroral oval  
123 at a period of  $\sim 10.7$  hours [*Nichols et al.*, 2008]. This causes the cusp to be observed twice  
124 within  $\sim 10$  hours, with the magnetosphere and field aligned currents observed inbetween.  
125 On the same day as one of the cusp events presented by *Arridge et al.* [2016], further evi-  
126 dence for reconnection was reported with the observation of a flux transfer event [*Jasinski*  
127 *et al.*, 2010] in an open field line region inbetween the magnetosphere and magnetosheath.

128 Here we present all the other cusp observations during the Cassini spacecraft era. We  
129 present analysis and comparison of a further eight cusp traversals on March 8th 2007  
130 (from now on referred to as ‘8MAR07’), May 25th 2008 (‘25MAY08’), August 3rd 2008  
131 (‘3AUG08’), September 24th 2008 (‘24SEP08’), November 23rd 2008 (‘23NOV08’), June  
132 14th 2013 (‘14JUN13’), July 24th 2013 (‘24JUL13’) and August 17th 2013 (‘17AUG13’).  
133 With the exception of 8MAR07, all the observations were in the northern hemisphere.  
134 We will also comment and compare to observations from January 21st 2009 (‘21JAN09’)  
135 [*Jasinski et al.*, 2014], and the January 16th and February 1st 2007 (‘16JAN07’ and  
136 ‘1FEB07’, respectively) [*Arridge et al.*, 2016].

137 The instrumentation used for this analysis will be described first, followed by the tra-  
138 jectory of the spacecraft. This is followed by an overview and description of all the cusp  
139 observations, and analysis of the reconnection location and the observed plasma compo-  
140 sition. Next, we explore possible solar wind correlations to the observations, and finally  
141 present our discussion and conclusions of the survey of observations.

## 2. Location of the Cusp Observations

142 Table 1 shows all the cusp events including the 21JAN09 event reported by *Jasinski*  
143 *et al.* [2014] and the 16JAN07 and 1FEB07 observations reported by *Arridge et al.* [2016].  
144 During the years of 2007 and 2008, the Cassini spacecraft performed a series of highly  
145 inclined orbits (peak absolute latitudes of  $>50^\circ$ ) where the trajectory provided the oppor-  
146 tunity to obtain cusp observations. In 2007 high-latitude northern observations occurred  
147 in the dusk and night-time sectors of the magnetosphere, which were less suitable for cusp  
148 detection. However the southern part of Cassini's trajectory was suitable for cusp cross-  
149 ings. In addition to the southern cusp observations presented by *Arridge et al.* [2016],  
150 the other southern cusp traversal is 8MAR07. The set of Cassini trajectories in 2008 and  
151 2013 favoured northern cusp observations.

152 The Cassini orbits during the times that were potentially suitable for cusp observations  
153 are shown in Figure 1, and are colour-coded by time period. The location of the actual  
154 cusp observations are marked by similarly colour-coded symbols. The cusp encounters  
155 described previously by *Jasinski et al.* [2014] and *Arridge et al.* [2016] are also indicated.  
156 Two of the events were located so close together that they can not be distinguished in  
157 Figure 1.

158 The trajectories were such that only one hemisphere in one quadrant (dawn–noon) was  
159 optimal to sample the cusp. In the northern hemisphere the cusp was observed at a range  
160 of altitudes and latitudes because Cassini had more trajectories that were favourable for  
161 cusp traversals. The southern hemisphere observations occurred on only one set of orbits  
162 and therefore all share a similar location.

### 3. Instrumentation

163 Observations from the following in situ instrumentation onboard the Cassini spacecraft  
164 will be presented: low-energy electrons and ions by the Electron and Ion Mass Spec-  
165 trometers (ELS and IMS respectively) which are part of the Cassini Plasma Spectrom-  
166 eter [CAPS; *Young et al.*, 2004], energetic electrons by the Low-Energy Magnetospheric  
167 Measurement System (LEMMS) which is part of the Magnetospheric Imaging Instru-  
168 ment [MIMI; *Krimigis et al.*, 2004], and the magnetic field by the magnetometer [MAG;  
169 *Dougherty et al.*, 2004].

170 ELS and IMS do not have a full  $4\pi$  steradian field of view, and so the CAPS instrument  
171 is mounted on an actuating platform that moves at a maximum rate of  $1^\circ$  per second  
172 to increase the angular coverage, and with full actuation can acquire  $\sim 2\pi$  sr in  $\sim 3.5$   
173 minutes. IMS has a time-of-flight analysis component which allows the determination of  
174 the ions mass per-charge.

175 To describe the ion flow direction, we present the IMS data as a function of look direction  
176 about the spacecraft (example shown in Figures 2d and e). This is a slice of the 3D  
177 distribution taken at a specified energy, normally corresponding to the peak count rate.  
178 The data are presented in a coordinate system centred on the spacecraft (the observer)  
179 which is facing Saturn (i.e. Saturn is at the centre of the plots), with  $\theta$  being a polar

180 angle away from Saturn ( $0^\circ$  points towards Saturn [ $\mathbf{S}$ ], and  $180^\circ$  points directly away from  
 181 Saturn).  $\theta$  is represented in the plots radially away from the centre, with  $90^\circ$  representing  
 182 the inner circle, and  $180^\circ$  representing the outer circle (and is a point in space behind  
 183 the spacecraft).  $\phi$  is an azimuthal angle measured around  $\mathbf{S}$ , where  $\phi = 0^\circ$  points in  
 184 the direction of  $\mathbf{S} \times (\boldsymbol{\Omega} \times \mathbf{S}) = \mathbf{O}$ , where  $\boldsymbol{\Omega}$  is the spin axis of the planet.  $\mathbf{A}$  completes the  
 185 right-handed set ( $\mathbf{A} = \mathbf{S} \times \mathbf{O}$ ). To explain this differently, if the reader can imagine they  
 186 are sitting on the spacecraft facing the planet, everything in front of them is within the  
 187 inner circle (with the inner circle representing the 'sides' of the observer where  $\phi < 90^\circ$   
 188 and  $\phi > 270^\circ$  is everything 'above', and  $90^\circ < \phi < 270^\circ$  is everything below the observer).  
 189 Everything behind the observer is between the inner and outer circles.

190 The MAG data are presented in the Kronographic-Radial-Theta-Phi (KRTP) coor-  
 191 dinate system (i.e. spherical polar coordinates). This coordinate system is spacecraft  
 192 centred on the magnetic field and planet-centred for the position of the spacecraft. The  
 193 radial ( $\mathbf{R}$ ) vector is directed in the planet-spacecraft direction, the azimuthal vector ( $\boldsymbol{\phi}$ ) is  
 194 positive in the direction of Saturn's rotation, and  $\boldsymbol{\theta}$  completes the right-hand set ( $\boldsymbol{\theta} = \mathbf{R} \times \boldsymbol{\phi}$ )  
 195 and is in the colatitudinal direction, positive southwards. In comparison to the ion-flow  
 196 coordinate system mentioned above,  $\mathbf{R} = -\mathbf{S}$ ,  $\boldsymbol{\phi} = \mathbf{A}$  and  $\boldsymbol{\theta} = -\mathbf{O}$ .

197 Also presented are solar wind properties extrapolated from 1 AU to 9 AU by the Michi-  
 198 gan Solar Wind Model (mSWiM) [Zieger and Hansen, 2008].

## 4. Observations

### 4.1. Evidence for Lobe and Dayside magnetopause reconnection - 8MAR07

199 The 8MAR07 event, shown in Figure 2, is very similar to the observations of the south-  
 200 ern cusp (16JAN07 and 1FEB07) that were presented by [Arridge et al., 2016]. Before

201 entering the cusp, CAPS does not observe plasma above the noise level, and this region is  
202 interpreted to be magnetically connected to the planet's polar cap [*Jasinski et al.*, 2014;  
203 *Arridge et al.*, 2016].

204 Once in the cusp, there are two energy-latitude dispersions, underlined in Figure 2a.  
205 The first is a 'reverse sense' dispersion. For the first dispersion, the ions are observed to  
206 be arriving from a higher latitude and from the sunward direction (panel d). A higher flux  
207 of ions are observed near the anti field-aligned direction (blue triangle) as well as from a  
208 direction 'below' the spacecraft where one would expect lobe reconnection to be occurring  
209 (the labels 'd' and 'e' show the time the corresponding angular distribution plots in panels  
210 d and e correspond to in the spectrogram in panel a). The second dispersion is a 'normal  
211 sense' dispersion, with a higher flux of ions arriving from an equatorward and a sunward  
212 direction, consistent with dayside subsolar reconnection. Therefore, the ion flow direction  
213 supports the interpretation of the location of the reconnection site from the dispersion  
214 orientation and not an oscillation of the cusp as observed by *Arridge et al.* [2016]. Of  
215 course, without multiple spacecraft, it is not possible to determine whether reconnection  
216 in these two locations was occurring at the same time or not. The dotted lines in panel  
217 a) are drawn to help understand the orientations of the two dispersions which start at  
218  $\sim 08:00$  UT and end  $\sim 10:20$  UT, before a change in the plasma temperature.

219 The two dispersions are also accompanied by a slight energisation of electrons between  
220 the two populations. Upon exiting the cusp, Cassini observed a narrow boundary layer  
221 (labelled 'BL') of plasma with decreasing density and an increasing energy, before en-  
222 tering the magnetosphere. In all of the southern cusp events (including those presented  
223 by *Arridge et al.* [2016]), there was a boundary layer observed before crossing into the

224 magnetosphere from the cusp. This was observed as a gradual increase (or decrease if  
225 entering the cusp from the magnetosphere) of the electron energy observed by ELS, and  
226 an increase in flux of energetic electrons in LEMMS. This is interpreted to be a high  
227 latitude extension of the low-latitude boundary layer [Arridge *et al.*, 2016].

#### 4.2. Cusp Observation signatures due to ‘Bursty’ dayside reconnection - 3AUG08

228 The data obtained from the 3AUG08 cusp crossing are presented in Figure 3. Unlike the  
229 southern observations the spacecraft was travelling planetward and poleward. There are  
230 two data gaps (in all the presented instruments) occurring at 12:10–12:50 and 16:22–18:03  
231 UT. At the beginning of the 3AUG08 event, energetic electrons in CAPS-ELS (panel a)  
232 and MIMI-LEMMS (panel c) are present until 14:45 UT. The energy distribution of these  
233 electrons is similar to those observed in the magnetosphere during the 21JAN09 event,  
234 and so the plasma is interpreted to be on closed magnetospheric field lines [Jasinski *et al.*,  
235 2014; Arridge *et al.*, 2016]. Before entering the cusp (at 14:47) the spacecraft passes  
236 through a region where the energy of the electrons is gradually decreasing, and the flux  
237 of the ions increases.

238 From 14:47 until 23:30 UT, Cassini traversed the cusp. IMS observed a high flux  
239 of ions (panel b), which had multiple energy-latitude dispersions. The data from the  
240 MIMI-LEMMS instrument (panel c) show high fluxes of energetic electrons up until the  
241 cusp crossing, with a significant decrease in the first ion dispersion observed, followed by  
242 background levels of counts in the rest of the cusp interval. A boundary layer is observed  
243 briefly for an hour before Cassini entered cusp, where low-fluxes of ions are observed as  
244 well as a slight decrease in electron energy. This is similar to the boundary layer reported

245 by *Arridge et al.* [2016], in their observations where a field aligned current is observed in  
246 a rotation in the  $B_\phi$  component of the magnetic field and (here at  $\sim 14:00$  UT). The start  
247 of the cusp is marked by the clear magnetosheath-like electron low-energy fluxes at the  
248 vertical dashed line.

249 There are four dispersions present in the data; the first is clearly observed at 14:47–16:22  
250 UT. The second and third dispersions are very close together, are difficult to separate and  
251 are tentatively identified as two separate dispersions. However the large increase in flux  
252 at  $\sim 18:35$  UT is designated to be the centre of the second dispersion at 18:15–18:50,  
253 with the third dispersion occurring at 18:50–20:40. The argument that these are two  
254 separate dispersions is supported by the flux measured by ELS as well as in the IMS  
255 measurements. The electron flux, as well as the energy, increases at the start of the third  
256 dispersion in comparison to the end of the second dispersion. At the same time there is  
257 also a step up in the energy of ions. Both of these observations suggest that these are two  
258 separate dispersions. If this was one dispersion, the electron flux would steadily decrease  
259 (similarly to the first dispersion) and the ions would also not increase in energy. Instead  
260 there is a clear passing of the spacecraft through two separate flux tubes filled with cusp  
261 plasma, with two different reconnection histories. All the dispersions are in the same  
262 sense, implying that the reconnection was taking place equatorward of the cusp and is  
263 also occurring in a ‘bursty’ or pulsed manner [*Lockwood et al.*, 2001; *Jasinski et al.*, 2014]  
264 due to the ‘stepped’ nature of the ion dispersions.

265 The magnetic field (panels d and e) is almost entirely in the radial direction, and is  
266 increasing significantly due to the planetward trajectory of the spacecraft. No diamagnetic  
267 depressions are seen during the cusp interval. There is a rotation in the  $B_\phi$  component at

268  $\sim 15:00$  UT coincident with the start of the cusp observations. This could be due to the  
269 crossing of the open-closed field line boundary marked by a field-aligned current (FAC)  
270 [*Bunce et al.*, 2008].

### 4.3. Isolated Cusp - 25MAY08

271 Presented in Figure 4 is an observation of a cusp not directly adjacent to the magneto-  
272 sphere, but isolated from it by a brief traversal of the polar cap. This event (25MAY08)  
273 was observed in the northern hemisphere (Cassini travelling polewards and planetward).  
274 The 25MAY08 event starts with the spacecraft (unlike in the previous cusps) in the polar  
275 cap, with no plasma observed within the detectability threshold of the instrumentation.  
276 The 8MAR07 event also starts in the PC, however what is different here is that this is a  
277 poleward pass, and the spacecraft entered the polar cap at  $\sim 23:30$  UT the previous day  
278 without seeing the cusp or a boundary layer there. The spacecraft exits the polar cap,  
279 passes through a brief boundary layer, characterised by hot and very tenuous plasma, and  
280 then proceeds through to cross the cusp.

281 In Figure 4, the spacecraft is already in the polar cap at 00:00 UT where electron flux  
282 was at the background level of the instrumentation. A very tenuous electron population  
283 is seen from  $\sim 00:20$  until 01:30 UT, with energies slightly higher than those in the cusp,  
284 representing a boundary layer before entering the cusp. At 01:30 until 02:30 UT the  
285 spacecraft observes dense, cold electrons in the cusp, and very high fluxes of ions with the  
286 typical energy-latitude dispersion.

287 For the first half an hour after exiting the cusp, the spacecraft observes very low fluxes  
288 above the background, and then for the following half hour, a higher energy population  
289 of electrons are observed in ELS and LEMMS (the high fluxes below  $\sim 25$  keV just after



290 05:00 and 08:30 UT are light contamination in the LEMMS instrument). Upon re-entering  
291 the cusp at 03:30 UT, the higher energy electrons continue to be observed for almost an  
292 hour in the cusp. There are a few bursts of increased flux in the plasma, the largest being  
293 associated with a small magnetic depression at  $\sim$ 04:10 UT. There is a clear energy-latitude  
294 dispersion with a gradual decrease in flux. At 06:40 UT, there is another dispersion  
295 with an increase in ion energy observed, before the cusp is exited at  $\sim$ 09:00UT and the  
296 spacecraft re-enters the polar cap.

297 Prior to 04:00 UT, the actuator was actuating only very slowly or not at all, so ion  
298 angular distributions are not available for the first dispersion event. At 04:00 UT full  
299 actuation resumed. Panel ii) presents the angular distributions of the ions during the  
300 second cusp dispersion, showing that the maximum ion flux was coming from the direction  
301 'below and behind' the spacecraft, consistent with travel inward along a reconnected field  
302 line as it is pulled northward through the cusp. The isolated nature of the cusp could  
303 hence be explained by an onset of reconnection after the spacecraft crossed the open-closed  
304 field line boundary.

#### 4.4. Tenuous Cusp Observations - 24SEP08 and 23NOV08

305 These two observations have been grouped together due to the similarity in the ELS  
306 and IMS data, and the relevant observations having short timescales. The data for the  
307 23NOV08 observations are presented in Figure 5 and those for the similar event 24SEP08  
308 are shown in the online supporting material (OSM). Before the cusp observation in Fig-  
309 ure 5, the spacecraft (similar to previous cusp intervals) crossed a boundary layer, where  
310 the energy of the electrons gradually decreased (observed by ELS and LEMMS panels a  
311 and c). The determination of the composition of the ions is difficult due to the low count

312 rate and small number of TOF accumulations available. However in the magnetosphere  
313 (03:54–05:36 UT) the water group percentage (of  $H^+$ ) was  $5.3\pm 0.4\%$ , which decreased to  
314  $1.3\pm 0.2\%$  in the overlapping bin (05:36–06:27 UT). There were no  $W^+$  counts above the  
315 background level in the cusp.

316 The start of the cusp observations was at 06:15 UT (for both events). High energy  
317 electrons are not observed in MIMI-LEMMS (panel c) during the 23NOV08 cusp crossing,  
318 but during the 24SEP08 observation they are. Two pulses of increased electron flux are  
319 observed bounding the cusp observations. This is the same as previous energetic electron  
320 observations on open field lines [*Roussos et al.*, 2015; *Mitchell et al.*, 2016; *Palmaerts*  
321 *et al.*, 2016], the reason for which previous reports have been unable to explain, but have  
322 shown that they are most likely triggered by reconnection.

323 In both days the cusp observations do not last longer than approximately 30 minutes.  
324 The September observation has a data gap, and the actual data are collected for no more  
325 than 10 minutes. However, the electrons are already lower in energy before the data gap  
326 occurs, implying that Cassini may already be in the cusp during the time of the data gap.  
327 Assuming the spacecraft is in the cusp during the data gap, the cusp interval would be  
328 approximately 20 minutes in duration.

329 The 23NOV08 observations show a weak “normal-sense” ion dispersion, with high en-  
330 ergies observed at lower latitudes, indicating reconnection occurring at the dayside sub  
331 solarmagnetopause (Figure 5). The 24SEP08 observation does not show any significant  
332 dispersion. The magnetic field orientation for both observations is the same; very strongly  
333 in the radial direction.

#### 4.5. Northern 2013 ‘Summer’ Cusp

334 The CAPS instrument was switched off permanently in 2012, due to a short circuit.  
335 Therefore there are no low energy particle observations for the high latitude orbits in 2013,  
336 and so another source of data must be a base for the search for the cusp during this period.  
337 MAG is used to locate magnetic field depressions which have been observed frequently  
338 at the terrestrial cusp as well as in some previous Saturn cusp examples including those  
339 presented by *Jasinski et al.* [2014] and more noticeably *Arridge et al.* [2016]. Depressions  
340 are not observed in the 3AUG08, 24SEP08 and 23NOV08 observations. This is due to  
341 their low radial distances ( $\sim 8-12 R_S$ ) from the planet, making the field more difficult to  
342 depress, as well as very low density plasma present in the 24SEP08 and 23NOV08 cusps.  
343 However the orbits during 2013 had large radial distances ( $>14 R_S$ ) where the cusp would  
344 most likely be observed, making it more likely that a detectable field depression would  
345 occur, if the cusp is traversed.

346 A study of the MAG data reveals three events with magnetic depressions in the cusp  
347 which will be described in this section (14JUN13, 24JUL13 and 17AUG13). All three  
348 northern observations occur with the spacecraft travelling equatorward in the pre-noon  
349 region, and are in the mid-to-high altitude range ( $14-18 R_S$ ). An overview of the 14JUN13  
350 cusp will be presented, followed by a description of the other events. The observations of  
351 the 24JUL13 and 17AUG13 events can be found in the OSM.

352 The cusp was identified using a combination of the MAG and LEMMS instruments.  
353 First of all, a decrease in magnetic field strength greater than any gradual change of the  
354 magnetic field strength (due to the spacecraft trajectory) identified the diamagnetic de-  
355 pression. Once a depression was located the energetic electron observations from LEMMS

356 were used to determine whether there was a decrease in (or a complete lack of) flux,  
357 similar to previous cusp examples. A magnetic depression with no energetic particles  
358 would provide evidence that there is a plausible plasma population below the LEMMS  
359 detectability threshold present (that would have been observed by CAPS had it still been  
360 activated) that is depressing the magnetic field.

361 The data from the 14JUN13 observation is presented in Figure 6, where the high energy  
362 electron (panel a) and magnetic field (panels b and c) data are shown. Before entering the  
363 cusp (identified for this example as the region of significant field depression), the spacecraft  
364 largely observes counts at the noise level for the energetic electron measurements, with a  
365 burst of electrons occurring just before the cusp at 18:50 UT, which coincides with a small  
366 rotation in the  $B_\phi$  component of the magnetic field. The magnetic field depression starts  
367 at 19:40 UT (with a field strength of  $\sim 11.5$  nT). At 21:00 UT, the depression reaches a  
368 minimum field strength of  $\sim 8.5$  nT. At 21:40, there is local drop in the magnetic field  
369 ( $\sim 1$  nT) and a burst of high energy electrons, which is interpreted as a brief entry into  
370 the boundary layer between the cusp and the magnetosphere (similarly observed in the  
371 25MAY08 encounter), before re-entering the cusp.

372 The cusp is exited at 22:10 UT, where the spacecraft enters a boundary layer of increased  
373 flux of energetic electrons. At 22:35 UT there is a clear crossing into the magnetosphere  
374 where LEMMS observes the highest fluxes of energetic electrons in this event. Passage  
375 deeper into the closed-field region is also marked by a slow rotation in  $B_\phi$  which could be  
376 the observation of a field aligned current inward of the open-closed field line boundary.  
377 The  $B_\phi$  rotation is also clearly seen upon entering the boundary layer at  $\sim 22:05$  UT.

378 Contrastingly, in the 24JUL13 event, it is not clear where the open-closed field line  
379 boundary is because there is no increase in flux of electrons observed in LEMMS when  
380 exiting or entering the cusp. This is similar to the 25MAY08 event, where the cusp appears  
381 to be 'isolated' in the polar cap. In the 24JUL13 we identify the cusp as the interval where  
382 the magnetic field is depressed. The cusp has a strong magnetic field depression and there  
383 are short bursts ( $\sim 30$  minutes) of increased flux an hour and two hours before the start  
384 of the cusp.

385 The 17AUG13 cusp observation is, in a manner, the opposite of the 24JUL13 obser-  
386 vation because it is bounded on both sides to the magnetosphere. There is a boundary  
387 layer observed for  $\sim 4$  hours before and  $\sim 2.5$  hours after the cusp interval, with slightly  
388 lower fluxes of energetic electrons than the magnetosphere. Whereas the magnetic field  
389 depression in the 14JUN13 observation is gradual, the 24JUL13 and 17AUG13 observa-  
390 tions both have large erratic changes in their depressions, which would probably be due to  
391 density changes in the low energy plasma. During the first half of the 17AUG13 magnetic  
392 field depression, there are background levels of electrons observed in LEMMS which is  
393 similar to the 2007 cusp observations, and would imply that the depression is not centred  
394 on the cusp, but on the boundary layer adjacent to the cusp. We identify the cusp in  
395 this example as the region with the lowest energetic-plasma fluxes observed by MIMI-  
396 LEMMS, as well as containing part of the depression. The boundaries have a rotation in  
397 the  $B_\phi$  component of the magnetic field, marking what we interpret to be the open-closed  
398 boundary with the magnetic signature of a FAC [e.g. *Bunce et al.*, 2008; *Jasinski et al.*,  
399 2014; *Jinks et al.*, 2014]. The depressions observed by Cassini are not always centred on  
400 the cusp; this is discussed in detail in a future paper (*Jasinski et al.*, in prep).

## 5. Energy-Pitch Angle dispersions and calculating the Distance to the Reconnection Site

401 For observations when CAPS was functioning, ion energy-pitch angle dispersions were  
 402 observed in the IMS data whilst in the cusp. From these energy pitch-angle dispersions  
 403 the distance to the reconnection site is determined for the cusp observations, by fitting the  
 404 *Burch et al.* [1982] model to the IMS energy-pitch angle data using the following equation:

$$E(\alpha_o, t) = \frac{m}{2t^2} \left[ \int_{s_i}^{s_o} ds / \sqrt{1 - \sin^2 \alpha_o (B(s)/B_o)} \right]^2 \quad (1)$$

405 where  $E$  is the energy of the ion,  $ds$  is the arc length along a model field line,  $s_o$  and  
 406  $s_i$  are the observation and injection points respectively,  $m$  is the particle's mass,  $B(s)$  is  
 407 the magnetic field strength along the field line,  $B_o$  is the magnetic field strength at the  
 408 observation point,  $\alpha_o$  is the observed pitch angle, and  $t$  is the transit time of the particle  
 409 from the injection site (via the mirror point for ions that have mirrored) to the observation  
 410 point. Both  $B(s)$  and  $B_o$  are obtained from the *Khurana et al.* [2006] magnetospheric field  
 411 line model. The solar wind dynamic pressure obtained from mSWiM for each event is  
 412 used as an input for generating the *Khurana et al.* [2006] model, as well as the location  
 413 of Cassini to extract  $B$ . mSWiM cannot propagate the IMF orientation of the upstream  
 414 solar wind, so the IMF input for the Khurana model is not changed between events  
 415 and is set to be in the northward direction.

416 The model was fit to the data using the Levenberg-Marquardt non-linear least squares  
 417 algorithm [Marquardt, 2009]. If the dispersion was not clear, the signal-to-noise ratio  
 418 was low or the model was unable to be successfully fitted, a calculation could not be  
 419 made. However for the successful fits, the results were all binned together within the

420 same energy-latitude dispersions, with the errors propagated, to give a final value for the  
421 distance to the reconnection site and its uncertainty.

422 The 25MAY08 result shows a distance to the reconnection site of  $16 \pm 3 R_S$  (for the  
423 second dispersion) which is similar to that calculated for 8MAR07 of  $16 \pm 1$  and  $15.6 \pm 0.4$   
424  $R_S$ . These imply a reconnection site poleward of the subsolar point. 24SEP08 produced  
425 a reconnection distance of  $21 \pm 5 R_S$ , similar to the 3AUG08 results of  $32 \pm 7$  and  $26 \pm 8$   
426  $R_S$  (for the first two dispersions), which reveal sites closer to the subsolar point, and  
427 more similar to the reconnection location reported for 21JAN09 [*Jasinski et al.*, 2014].  
428 No results could be obtained for 23NOV08. A full table of the results can be seen in the  
429 OSM.

430 The calculated field-aligned distances were traced along field-lines using the *Khurana*  
431 *et al.* [2006] magnetospheric field-line model and the location of the reconnection site  
432 was estimated. The results can be seen in Figure 7, where the locations are shown as if  
433 viewed from the Sun in the Y-Z plane (in the KSM co-ordinate system). The estimated  
434 sites (for reconnection) occur over a large range of locations, including low and high  
435 latitudes. The large calculated field aligned distances ( $\sim 50 R_S$ ) for the 16JAN07 and  
436 1FEB07 events (as well as the latter calculations for 21JAN09) are more feasible with an  
437 expanded magnetosphere. For the 16JAN07 and 1FEB07 events, if lower projections for  
438 the solar wind dynamic pressure were to be used (than the solar wind model predicts), then  
439 these locations would move equatorward. The distribution of the reconnection locations  
440 is largely centered slightly poleward (towards the north) of the subsolar point, with only  
441 the 21JAN09 event located very far south of the subsolar point.

## 6. Plasma composition in the Cusp

When analysing the ion composition in the cusp and the adjacent magnetosphere using IMS, two ratios for comparison can be used: a mass-per-charge of 2 amu/q to ionised hydrogen ratio ( $[m/q=2]/H^+$ ), and ionised water group to hydrogen ion ratio ( $W^+/H^+$ ). The water group ions include:  $O^+$ ,  $OH^+$ ,  $H_2O^+$ , and  $H_3O^+$ . The water group originate principally from Saturn's icy moon Enceladus (as well as the other icy moons), and therefore we expect higher percentages of these ions in the magnetosphere in comparison to plasma entering the cusp from a magnetosheath origin. Both  $He^{++}$  and  $H_2^+$  have a mass-per-charge of 2, but we would expect the ions to be  $H_2^+$  in the magnetosphere with approximate percentages relative to  $H^+$  of  $\sim 10\text{--}20\%$  or more, peaking at a distance of Titan's orbit ( $20R_S$ ) [*Thomsen et al.*, 2010] which is predicted to be the source of these ions [e.g. *Cui et al.*, 2008]. Titan is the dominant source, but water from Enceladus, Rhea and Saturn's rings also contribute to the  $H_2^+$  found in the Saturnian magnetosphere [*Tseng et al.*, 2011]. Cold  $H_2^+$  and  $W^+$  have higher concentrations at the equator, contained there due to centrifugal forces, therefore reducing the abundances at higher latitudes [*Persoon et al.*, 2009]. However, lower abundance values for  $m/q=2$  ions, would suggest that they are  $He^{++}$  of a solar wind origin [ $\sim 4\%$ , e.g. *Ogilvie et al.*, 1989]. The data reduction software written by *Reisenfeld et al.* [2008] is used to produce the ion counts from the time-of-flight composition data from IMS.

The magnetosphere adjacent to the cusp has a variety of  $W^+/H^+$  percentages ranging from  $3.5 \pm 0.4\%$  (16JAN07) to  $32.6 \pm 1.2\%$  (3AUG08). These percentages are much lower in the cusp with the lowest being  $0.29 \pm 0.02\%$  and the highest  $1.3 \pm 0.2\%$  (25MAY08 and 23NOV08 respectively). The  $[m/q=2]/H^+$  in the magnetosphere adjacent to the cusp



464 has percentages from  $8.3\pm 0.27\%$  to  $28.2\pm 0.1\%$  (8MAR07 and 3AUG08, respectively),  
465 suggesting these ions are  $H_2^+$ . In the cusp these  $[m/q=2]/H^+$  values are lower, ranging  
466 between  $1.5\pm 0.05$  and  $4.76\pm 0.03$  (8MAR07 and 3AUG08 respectively), which suggest  
467 that this component of the plasma is  $He^{++}$  and of a solar wind origin. A full table of the  
468 compositional analysis can be seen in the OSM.

## 7. Survey of upstream conditions using mSWiM

469 Unlike at the terrestrial magnetosphere, where there are spacecraft upstream of the  
470 magnetosphere observing the conditions in the solar wind (SW), it is a lot more diffi-  
471 cult to correlate SW changes to processes in the magnetosphere with a single spacecraft  
472 such as Cassini. Therefore, solar wind propagation models are used as proxy upstream  
473 monitors for Saturn's magnetosphere. mSWiM is an MHD model of predicted solar wind  
474 conditions at various bodies of interest, propagated from spacecraft observations at 1AU,  
475 from either Earth, Stereo A or Stereo B spacecraft [Zieger and Hansen, 2008]. The most  
476 accurately predicted solar wind property of the model is the solar wind velocity, followed  
477 by the magnitude of the IMF and density. Ideally one would also like to use the normal  
478 component (in RTN coordinates) of the IMF ( $B_{Normal}$  is the component closest to a plan-  
479 etary Z axis) to test whether reconnection is controlled by the orientation of the IMF as  
480 for the Earth. However,  $B_{Normal}$  is very inaccurate having shown insignificant correlation  
481 between model and observations. The propagations are most accurate for observations  
482 where the selected spacecraft near Earth orbit (at 1 AU) and Saturn were aligned within  
483 75 days of apparent opposition. It has been shown that the uncertainty in predicted ar-  
484 rival time near apparent opposition is  $\pm 15$  hours. Propagations outside these alignments

485 (75 days) are not as accurate but are, however, still statistically significant [*Zieger and*  
486 *Hansen, 2008*].

487 The following events occur within 75 days of apparent opposition: 16JAN07 (54 days  
488 from apparent opposition), 1FEB07 (38 days), 8MAR07 (3 days), 25MAY08 (38 days),  
489 21JAN09 (31 days), 14JUN13 (17 days), 24JUL13 (53 days) and 17AUG13 (69 days). The  
490 following events occurred outside 75 days of apparent opposition: 3AUG08 (108 days),  
491 24SEP08 (150 days) and 23NOV08 (90 days).

492 The solar wind dynamic pressure ( $P_{RAM}$ ) indicates whether the magnetosphere is being  
493 compressed, whilst a high Alfvénic Mach number,  $M_A$ , (dependent on low magnetic field  
494 strengths, high densities and high velocities) in the solar wind would produce a high- $\beta$   
495 magnetosheath, making it more likely for reconnection to be suppressed and to only occur  
496 when the magnetic field lines are near completely anti-parallel [*Slavin et al., 1984; Masters*  
497 *et al., 2012*]. The results are presented in Figure 8, with  $P_{RAM}$  and  $M_A$  presented in black  
498 and red respectively, for ten days on either side of each event (except for 16JAN07 and  
499 1FEB07 which are presented together in panel a). The number of days from apparent  
500 opposition can be found in brackets for each observation.

501 For almost half of the cusp observations [16JAN07 and 1FEB07 (Figure 8a),  
502 24SEP08 (c) and 23NOV08 (f) and 24JUL13 (i)] there is a significant increase in the  
503 ram pressure, especially for 24SEP08 which has the largest peak of  $\sim 0.15$ nPa. These  
504 would correspond to large compressions of the magnetosphere, which have been shown to  
505 provide more favourable conditions for dayside reconnection [e.g., *Jackman et al., 2004*].  
506 However it is also important to note that two of these days also have the longest separation  
507 from apparent opposition (all  $>75$  days).

508 Three of the other six days (8MAR07, 25MAY08, 21JAN09) do not occur during peaks  
509 but they do occur during modest increases in ram pressure. 25MAY08 is at the start of  
510 a large pressure increase, with a modest increase having already occurred. However the  
511 increases for 8MAR07 and 21JAN09, are extremely modest and less significant. The other  
512 three days occur during periods of very low predicted ram pressures.

513 It is interesting to see that for 16JAN07, 1FEB07, 24SEP08 and 23NOV08,  $M_A$  is  
514 at a peak or very large ( $>40$ ), meaning the reconnection that occurred to produce the  
515 entry of solar wind plasma through the cusp must have occurred at a location on the  
516 magnetopause where the magnetic shear was very large. The lowest  $M_A$  of  $\sim 10$  was  
517 observed for 21JAN09. For the other five observations  $M_A$  was modest, averaging  $\sim 20$   
518 and did not occur during significant peaks or troughs. This supports the conclusion that  
519 cusp detections can be found during both compressed and more expanded conditions as  
520 reported by *Arridge et al.* [2016].

## 8. Discussion and Conclusions

521 Complementing the three cusp observations (16JAN07, 1FEB07 and 21JAN09) pre-  
522 viously reported [*Jasinski et al.*, 2014; *Arridge et al.*, 2016], a further eight more cusp  
523 observations in the in situ data have been presented. The 16JAN07 and 1FEB07 events  
524 both observed the cusp twice, which brings the total of cusp crossings to 13. The ob-  
525 servations display considerable variability, with different types of energy dispersions and  
526 plasma conditions observed, various upstream solar wind conditions, and a disparity in  
527 the strength of diamagnetic depressions.

528 Eleven of these crossings are adjacent to a boundary layer of mixed plasma before enter-  
529 ing the magnetosphere, and are similar to terrestrial observations [e.g. *Dunlop et al.*, 2005].

530 The outbound crossings of the second cusps in 16JAN07 and 1FEB07 (which have the  
531 magnetosphere on both sides of the observation) however, do not have a boundary layer,  
532 and instead pass directly into the magnetosphere. In contrast the 17AUG13 observation  
533 does have a boundary layer present on either side of the event.

534 The ion compositions in the cusp and the adjacent magnetosphere show that the  
535  $[m/q=2]/H^+$  ratio is much higher in the magnetosphere ( $8.3\pm 0.27-28.2\pm 0.1$ ) which is  
536 in agreement with other studies that suggest this region contains  $H_2^+$  [*Thomsen et al.*,  
537 2010]. In the cusp this ratio is much lower (average of  $2.8\pm 0.2$ ) which is similar to solar  
538 wind observations and therefore the  $m/q=2$  ion is more likely to be  $He^{++}$ . The average  
539  $He^{++}$  to  $H^+$  abundance ratio in the solar wind is  $\sim 3\%$  and  $\sim 5\%$  at solar minimum and  
540 maximum respectively [*Ogilvie et al.*, 1989], which is similar as the values found in the  
541 cusp. These authors reported very occasional abundance ratios of  $He^{++}/H^+$  of  $\sim 10\%$ ,  
542 however these occurrences are very rare. The water group to proton ( $W^+/H^+$ ) ratio, is  
543 also much higher in the magnetosphere in comparison to the cusp, as expected (the moon  
544 Enceladus is the main source of water group ions). Some non-zero values of  $W^+$  are found  
545 in the cusp, which is interpreted to be plasma that has not drained out of the newly  
546 opened flux tubes.

### 8.1. Ion energy-latitude dispersions

547 The variety of the characteristics of the plasma observations suggest different processes  
548 ongoing during the different cusp observations. The most striking is the first observation  
549 of lobe reconnection occurring during 8MAR07 (Figure 2). A “reverse-sense” ion energy  
550 latitude dispersion is observed. This is then followed by a “normal-sense” dispersion. This

551 is the only example we present which has reconnection occurring at two different locations  
552 during the same cusp interval.

553 Multiple ion energy-latitude dispersions are observed during the 25MAY08 event. The  
554 presence of magnetospheric plasma (high energy electrons in panels Figure 4a,c) between  
555 the first and second dispersions, shows that this may be a temporal observation of the cusp  
556 motion over the spacecraft, and not two separate cusps. A similar observation was found  
557 at Earth [e.g. *Zong et al.*, 2008; *Escoubet et al.*, 2013], where a double cusp was observed,  
558 and was shown to be the motion of the cusp due to a change in the IMF orientation. *Wing*  
559 *et al.* [2001] however have shown that two cusp regions can be present simultaneously at  
560 Earth. Without multiple spacecraft to test whether the cusp has moved, this hypothesis  
561 cannot be verified.

562 However, the continuous observation of the cusp during the second and third consecutive  
563 dispersions is different to that reported above (at Earth). The multiple dispersions here are  
564 not due to a motion of the cusp because there is no change in the ion dispersion direction.  
565 If the cusp had moved, the ion energy would be gradually dispersed in the opposite sense  
566 on neighbouring intervals. However there is a 'step-up' in the energy which shows that  
567 'pulsed' reconnection is also occurring on this day. The 3AUG08 event also displays  
568 multiple dispersions, similar to the 21JAN09 event [*Jasinski et al.*, 2014]. The changes  
569 in the plasma regime whilst in the cusp, as well as 'step-like' energy-latitude dispersions  
570 in the ion observations suggest that reconnection is pulsed at the magnetopause, and not  
571 steady [*Lockwood and Smith*, 1994]. The locations of the 25MAY08 and 3AUG08 events  
572 are very similar, and the energy-pitch angle analysis reveals a similar field-aligned distance  
573 to the reconnection site. This finding indicates the possibility that the same area of the

574 magnetopause is being reconnected for these two events. The 25MAY08 and 24JUL13  
575 observations differ from all the others in that the spacecraft is already on open field lines  
576 mapping to the polar cap prior to entry into the cusp. In the other cusp observations  
577 however, there is a definite transition from magnetospheric plasma on closed field lines, to  
578 the cusp plasma on open field lines. This comparison shows that the spacecraft is already  
579 traversing open field lines at the start of the observations for 25MAY08 and 24JUL13.  
580 This suggests that there is motion of the cusp and magnetospheric field lines over the  
581 spacecraft.

582 The cusp event most similar to 21JAN09 [*Jasinski et al.*, 2014], is the 3AUG08 observa-  
583 tion. The trajectory for 3AUG08 explores a greater region of local time in comparison to  
584 21JAN09, and so the observations show that the cusp is spread in local time. Therefore  
585 the energy-time dispersions for 3AUG08 are more likely to contain an element of azimuthal  
586 dispersion as the open field line sub-corotates, as well as the usual poleward dispersion  
587 associated with analogous events at Earth. The Earth's cusp can also be spread in local  
588 time when there is a strong  $B_y$  component of the IMF. However, without accurate solar  
589 wind data at Saturn, this cannot be investigated further. For the 21JAN09 event, where  
590 a subsolar reconnection site is predicted, it is much more likely that azimuthal convection  
591 at Saturn is the cause. If the IMF has a large  $B_y$  component, then reconnection will most  
592 likely be suppressed [*Masters et al.*, 2012], at the subsolar point. Reconnection will most  
593 likely occur when there are large local shear angles (so a small  $B_y$  component), decreasing  
594 the likelihood that the azimuthal motion is due to the IMF  $B_y$ . However as the mag-  
595 netosheath magnetic field is draped along the magnetopause, reconnection could occur  
596 away from the subsolar point where the IMF field has a  $B_y$  component, and therefore

597 azimuthal motion of the cusp could be occurring similarly to Earth observations. *Badman*  
598 *et al.* [2013] have previously reported reconnection occurring with the IMF having a  $B_y$   
599 component.

600 The 24SEP08 and 23NOV08 events both present very tenuous plasma observations. The  
601 low ion counts make it difficult to discern an energy-latitude dispersion. There is a possible  
602 dispersion in the 23NOV08 event, but the low signal-to-noise makes it inconclusive. These  
603 two observations are very similar to each other but not to the other events. One of the  
604 reasons these observations are so short in duration could be due to the spacecraft traversing  
605 the cusp with a large impact parameter. The other could be that reconnection had only  
606 just occurred at the magnetopause, and so the spacecraft entered the polar cap quite soon  
607 after the start of the cusp.

## 8.2. Location of Magnetic reconnection

608 The field-aligned distance to the reconnection site was calculated for each energy-pitch  
609 angle dispersion, and has produced a varied set of results. The results had a range of values  
610 of  $16 \pm 1$  to  $51 \pm 2 R_S$ . The median value was  $29.5 R_S$  and the lower and upper quartiles  
611 values were  $18.5$  and  $47.5 R_S$ , respectively. The results show that reconnection occurred  
612 at various areas along the magnetopause, with most of the events having reconnection  
613 locations polewards of the subsolar regions. This is in agreement with *Desroche et al.*  
614 [2013] who modelled the regions more likely to be reconnected along the magnetopause  
615 (as well as independent MHD simulations of the IMF effect on Saturn's magnetosphere  
616 by *Fukazawa et al.* [2007]) and showed that such regions would be generally poleward  
617 of the subsolar point. As mentioned above, most of the calculated reconnection sites  
618 are in agreement with *Desroche et al.* [2013], but most of the 21JAN09, as well as the

619 SMAR07 reconnection locations lie outside the predicted areas found by *Desroche et al.*  
620 [2013] (i.e. southward of the subsolar point). However, the simulations by *Desroche et al.*  
621 [2013] are for southern summer conditions (only three of our events are during this time)  
622 as well as for local IMF orientations only near the ecliptic plane. Without knowledge of  
623 the upstream IMF, it is difficult to make any more detailed comparison between their  
624 predictions and our calculated reconnection locations for 8MAR07 and 21JAN09. Our  
625 results are similar to the model reconnection locations for a northward IMF presented by  
626 *Masters* [2015]. Our results agree with *Masters* [2015] and show that the cusp maps to  
627 reconnection sites occurring over a wide range of locations along the magnetopause.

### 8.3. Solar wind correlation

628 All of the cusp observations have been compared to the propagated upstream solar  
629 wind data from the propagation model, mSWiM. Eight (16JAN07, 1FEB07, 24SEP08,  
630 23NOV08, 24JUL13, JAN 09, 25MAY08) out of eleven cusp events occurred during in-  
631 creases in the ram pressure of the solar wind to within 15 hours, five of which occur during  
632 significant peaks, while the other three coincide with modest increases in ram pressure.  
633 It is worth noting that two of these events occur 75 days after apparent opposition, and  
634 so the propagated parameters are less accurate [*Zieger and Hansen, 2008*]. An increase in  
635 ram pressure produces a compression of the magnetosphere which has been shown to pro-  
636 vide more favourable conditions for reconnection to occur [*Jackman et al., 2004*]. Three  
637 of these eight observations also do not have high Alfvénic Mach numbers ( $M_A$ ), resulting  
638 in a lower  $\beta$  magnetosheath. Hence for the other observations with high  $M_A$ , the recon-  
639 nection that led to the cusp events must have occurred at a location on the magnetopause  
640 where the local magnetic shear was extremely large, i.e. close to  $180^\circ$  [*Slavin et al., 1984*;



641 *Masters et al.*, 2012]. Of the other four observations that do not coincide with increases  
642 in ram pressure, only one (17AUG13) had an  $M_A$  of  $\leq 20$ . The other three did not occur  
643 during peaks or troughs in  $M_A$ . The  $B_{Normal}$  component of the IMF is not presented as it  
644 is the least accurate of the variables produced by mSWiM, and therefore it is not possible  
645 to correlate the orientation of the predicted IMF to the observations. However for periods  
646 of high  $M_A$ , one would assume that the local shear angle at a reconnection site would  
647 have to be very high or anti-parallel.

648 The results show that reconnection and subsequent cusp observations can occur during  
649 a variety of solar wind conditions. However the presence of so few cusp examples during  
650 overlapping spacecraft orbits imply that the necessary solar wind conditions required for  
651 reconnection to occur are not as common at Saturn as at Earth, supporting the conclusion  
652 of *Masters et al.* [2012], that reconnection at Saturn is often suppressed to only occur when  
653 the magnetic shear of the two magnetic fields is very high (something that can not be  
654 investigated with mSWiM data. This finding also supports the open flux investigation  
655 reported by *Badman et al.* [2013]. From a large set of auroral images, the authors found  
656 that although Saturn has a similar relative amount of open flux (2-11%) as Earth, the  
657 usual percentage of flux that was closed in between observations is much lower ( $\sim 13\%$ ,  
658 whilst at Earth  $\sim 40-70\%$ ). Assuming that, over adequately large timescales, the amount  
659 of flux opened is equal to the amount closed, opening of flux occurs during fewer events  
660 or at a lower rate than at Earth. The low number of cusp observations could also, in part,  
661 be due to the small spatial size of the cusp at Saturn. If opening of flux occurs at a lower  
662 rate, one would expect the spatial extent of the cusp to be lower, and therefore it would  
663 be more likely for Cassini to 'miss' it.

#### 8.4. Energetic electron events

664 One-hour-period bursts of high energy ( $\sim 100$  keV) electron flux can be seen for some  
665 of the magnetospheric observations (adjacent to the cusp). This is most obviously ob-  
666 served in the CAPS-ELS observations for the 3AUG08 event whilst in the magnetosphere  
667 adjacent to the cusp, in the MIMI-LEMMS observations for the 24JUL13 event between  
668 21:00 and 23:00 UT the day before, and in the 1FEB07 observation between 20:00 and  
669 23:00 UT. These energetic electrons (LEMMS) are also observed on open field lines in  
670 the cusp for the 24SEP08 and 14JUN13 events. During both events periodic pulses are  
671 occasionally observed. Energetic electrons, usually associated with magnetosphere, are  
672 not expected to be observed on open fields because once the field line is open to the solar  
673 wind, these electrons will quickly ‘drain’ out of the magnetosphere. For the 24SEP08  
674 these electrons have pitch angles of both field and anti-field aligned, which would prob-  
675 ably require energization above and below the observation point, or at the reconnection  
676 site; something that we cannot quantify in this paper. Similar observations of energetic  
677 electrons have been found to occur on open field lines [*Roussos et al., 2015; Mitchell et al.,*  
678 *2016; Palmaerts et al., 2016*]. Statistical surveys have shown that these electrons map to  
679 the dayside magnetopause [*Roussos et al., 2015; Palmaerts et al., 2016*]. Their cause  
680 is currently not understood; they have been suggested to be related to reconnection pro-  
681 cesses. Their observations in our events on open field lines in the cusp are also unusual  
682 and unexplained. However, considering their observation occurs during cusp crossings  
683 which are evidence for reconnection, we agree with previous reports that they may be  
684 triggered by reconnection.

## 8.5. Conclusions and further work

685 A further eight magnetospheric cusp traversals at Saturn have been presented, which  
686 complement previous observations [*Jasinski et al.*, 2014; *Arridge et al.*, 2016]. The ob-  
687 servations display considerable variability in their characteristics, such as the ion energy  
688 latitude dispersions, the propagated upstream solar wind conditions, the plasma compo-  
689 sition and the field-aligned distance to the reconnection site. All the cusp events, except  
690 for one, occur where the reconnection site is at the subsolar point. The 8MAR07 cusp  
691 event shows evidence for both subsolar and lobe reconnection occurring on the same day.  
692 Evidence for bursty or pulsed reconnection was presented similar to the event presented  
693 by *Jasinski et al.* [2014], and was observed in the ion energy latitude dispersions. However,  
694 other events also show similarity to the more steady energy-latitude dispersions presented  
695 by *Arridge et al.* [2016]. The field-aligned distance to the reconnection site was also found  
696 to vary significantly between events. The solar wind propagation shows that the cusp is  
697 present for both compressed and expanded magnetospheric conditions, as well as a variety  
698 of solar wind Alfvénic Mach numbers.

699 Strong diamagnetic depressions in the cusp have been widely studied and are often  
700 observed at Earth [e.g. *Zhou et al.*, 2001; *Trattner et al.*, 2012] as well as at Mercury  
701 [*Winslow et al.*, 2012]. Diamagnetic depressions at Earth have been correlated with highly  
702 energetic particles in the cusp [e.g. *Chen et al.*, 1997, 1998; *Nykyri et al.*, 2011a, b]. Such  
703 depressions are observed in eight out of the 11 events that have so far been identified at  
704 Saturn. Some statistical studies impose criteria on the depth of a diamagnetic depression  
705 in order to classify it as such. *Niehof et al.* [2010] use a 20% decrease in magnetic field  
706 strength. Using this criterion some of our observed depressions would not be classified as

707 a diamagnetic depression in our study. The strength of the depression has been suggested  
708 to be correlated to the reconnection rate [*Slavin et al.*, 2014], and this could mean that  
709 lower reconnection rates (which are expected at Saturn) could thus result in less significant  
710 magnetic field depressions. To try and elucidate the physics of the diamagnetic depressions  
711 in Saturn's cusp and shed further light on magnetopause reconnection at Saturn, another  
712 investigation will focus on the diamagnetic depressions.

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**Table 1.** Locations and times of observations for all the cusps presented in this paper as well as *Jasinski et al.* [2014] and *Arridge et al.* [2016].

Cusp	Date	Time (UT)	Distance ( $R_S$ )	Latitude ( $^\circ$ )	Local Time
16	JAN07	09:56 – 18:04	12.6	-54.5 – -43.4	10:10 – 11:39
1	FEB07	15:40 – 26:46	15.6 – 16.0	-56.0 – -46.8	09:39 – 11:14
5	MAR07	08:03 – 10:50	13.8 – 14.2	-43 – -40.8	11:22 – 11:42
25	MAY08	01:33 – 07:47	11.6 – 9.3	56.4 – 64.4	13:16 – 14:26
24	SEP08	06:15 – 07:12	10.6 – 10.3	60.6 – 62.2	12:32 – 12:41
23	NOV08	06:16 – 06:47	12.2 – 12.2	62.0 – 62.7	12:53 – 12:57
3	AUG08	14:47 – 22:59	11.1 – 8.2	58.7 – 72.7	12:32 – 14:55
21	JAN09	11:00 – 19:00	16.5 – 15.5	42.3 – 50.4	11:37 – 12:06
14	JUN13	19:40 – 22:10	14.3 – 14.6	39.8 – 37.5	10:51 – 11:02
24	JUL13	00:00 – 05:30	15.4 – 15.3	51.37 – 55.03	10:28 – 11:20
17	AUG13	14:00 – 16:05	18.5 – 18.4	38.0 – 33.0	10:13 – 10:22

**Figure 1.** The trajectory of the spacecraft and locations of the cusp for the different orbits and observations. The orbit of the satellite is presented for four different time periods (shown in the legend) with the location of the cusp observation displayed as a triangle of the same colour as the orbit. The 21JAN09 and AUG 08 observations are displayed as stars to distinguish them from the 24SEP08 and 23NOV08 events, which are all located on the same set of orbits. The trajectories are presented in the Kronocentric Solar Magnetospheric (KSM) co-ordinate system, where X points towards the Sun, Y equals the normalised cross product of the magnetic dipole direction with X, and Z completes the right-hand set (and lies in the plane formed by X and the magnetic axis). The average magnetopause location (dotted) at  $\sim 22R_S$  (the lower value from the bimodal distribution found by *Achilleos et al.* [2008]) is also shown (calculated using the *Kanani et al.* [2010] model). The X-Y and Y-Z planes are shown in the bottom-left and bottom-right respectively.

**Figure 2.** A high-time resolution spectrogram of the ion observations from IMS displaying the two different energy-latitude dispersions (dotted and underlined in panel a to guide the eye) from the 8MAR07 event (panel a). Panel: b) omnidirectional electron differential energy flux ('DEF') from ELS; c) magnetic field magnitude (MAG); d) and e) show the angular distributions of the ions at a point in each dispersion (the times relative to the spectrogram are shown with arrows, see text for more details). The blue and red triangles in d) and e) represent where the ions would be observed if they were travelling in an anti-field aligned and field-aligned directions, respectively.

**Figure 3.** Observations of 3AUG08, with the cusp observed at 14:45–23:45 UT. From top to bottom: a) electrons from CAPS-ELS, b) ions (all anodes summed) from CAPS-IMS, c) high-energy electrons from MIMI-LEMMS (the high fluxes in up to the  $\sim 25$  keV energy level are due to light contamination of the instrument), d) the three components of the magnetic field in KRTP coordinates from MAG and e) the magnitude of the magnetic field also observed by MAG.

**Figure 4.** Observations from the 25th of May 2008, with the cusp observed at 01:30–02:30 and 03:30–07:45 UT. From top to bottom: i and ii) show the ion angular distributions during the first two ion dispersions, a) electrons from CAPS-ELS, b) ions from CAPS-IMS, c) high-energy electrons from MIMI-LEMMS, d) the three components of the magnetic field in KRTP coordinates from MAG and e) the magnitude of the magnetic field also observed by MAG.

**Figure 5.** Observations of the 23NOV08 event, with the cusp observed at 06:15–06:45 UT. This figure is in the same format as Figure 3.

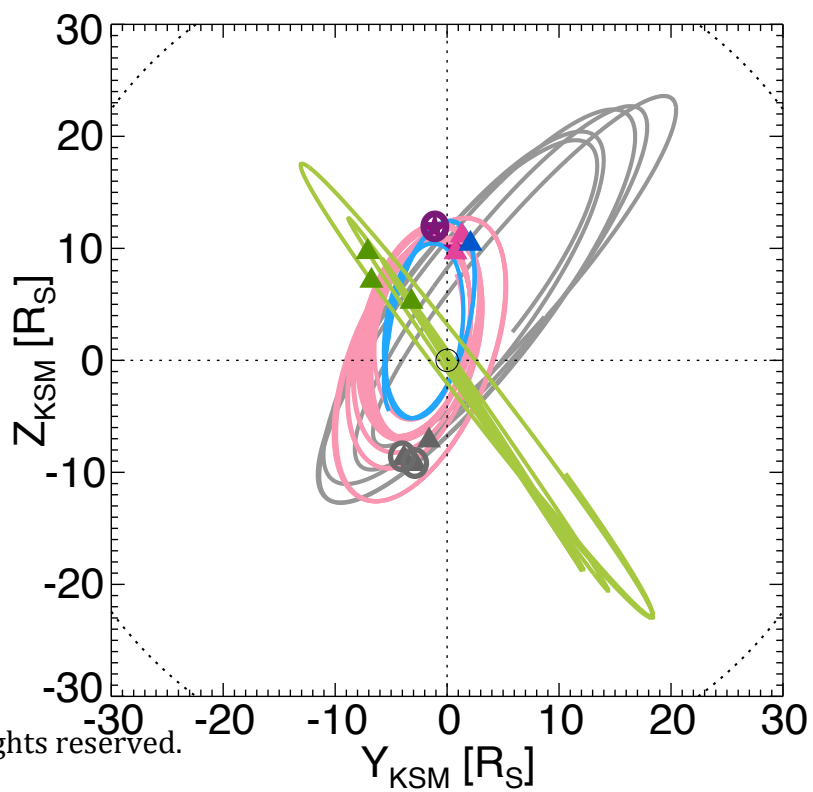
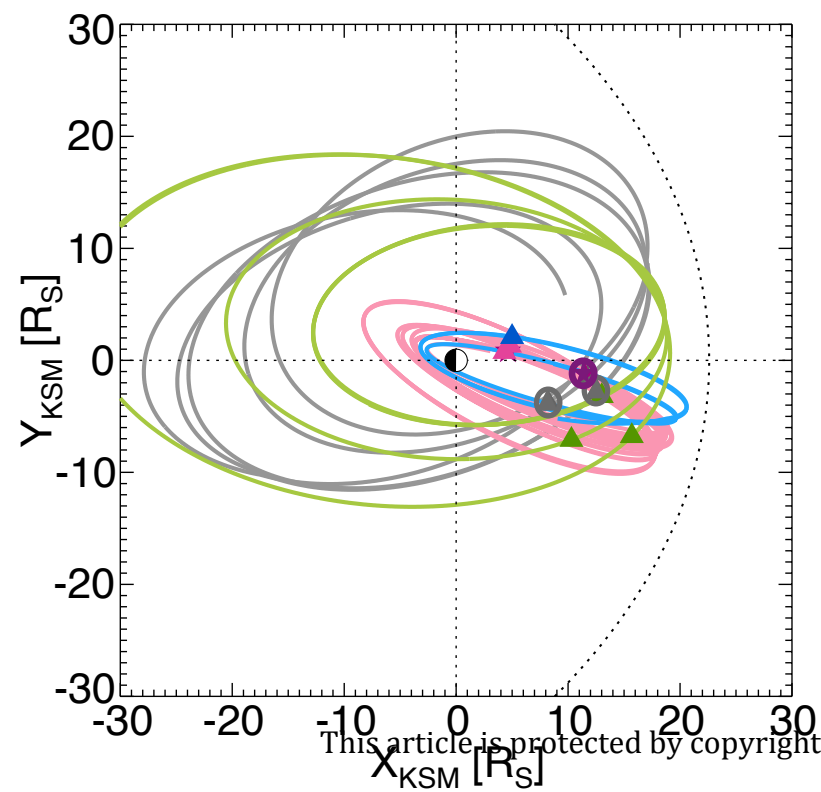
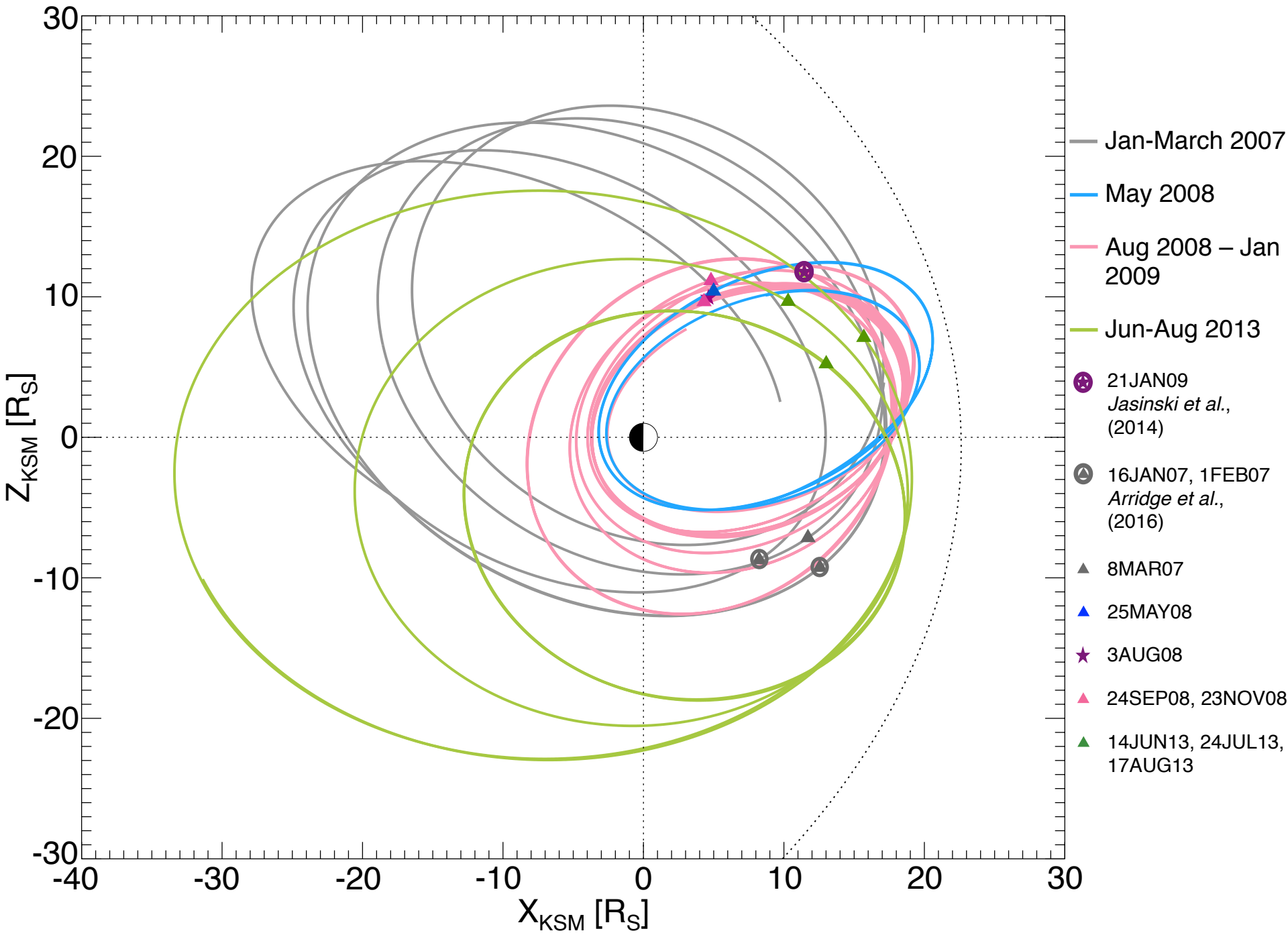
**Figure 6.** Observations from the 14th of June 2013, with the cusp observed at 19:40–22:35 UT. From top to bottom: a) high-energy electrons from MIMI-LEMMS, b) the three components of the magnetic field in KRTP coordinates from MAG and c) the magnitude of the magnetic field also observed by MAG.

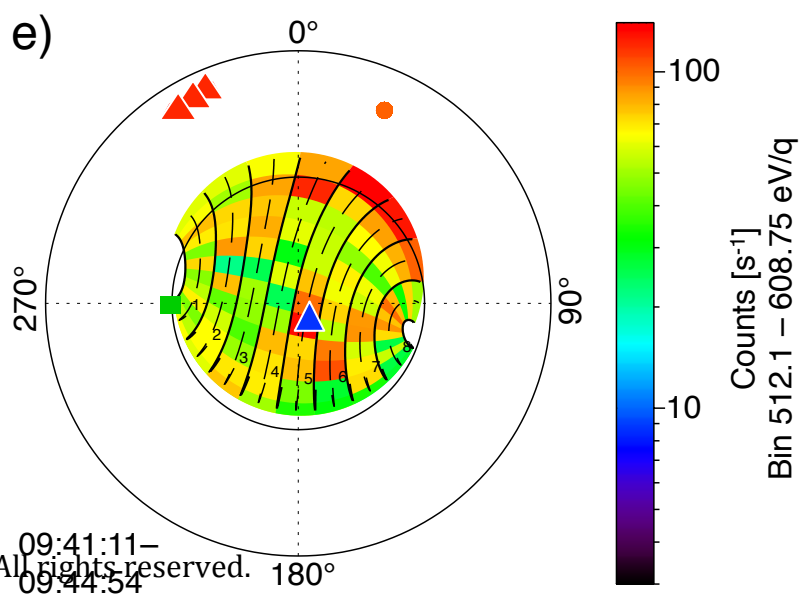
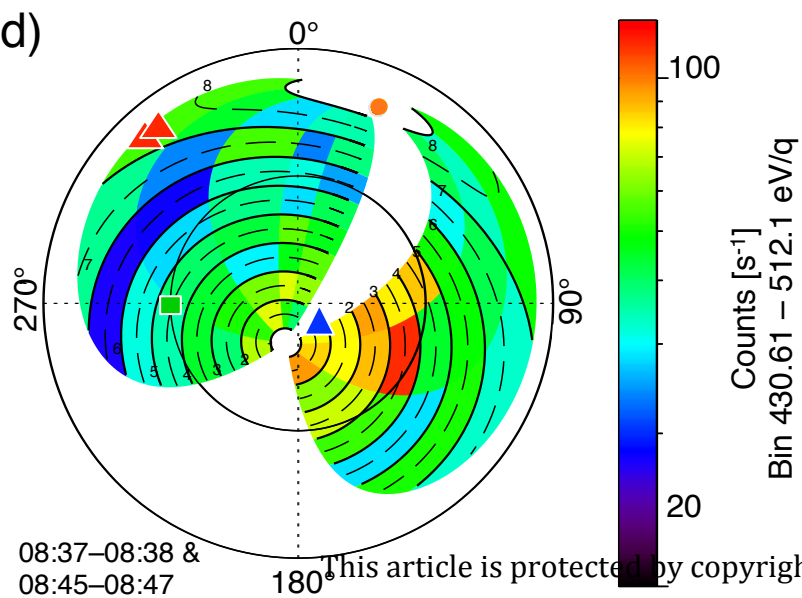
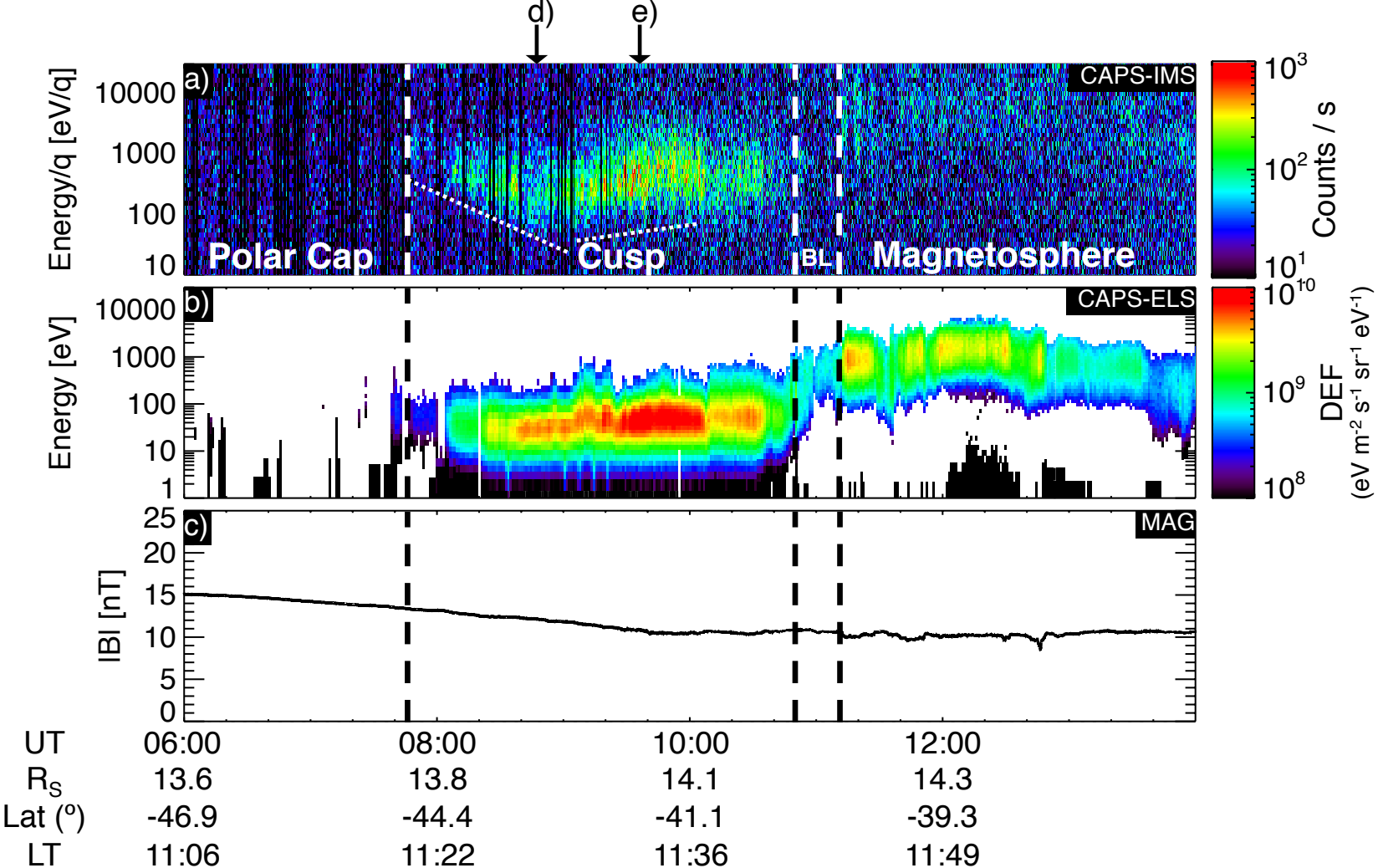


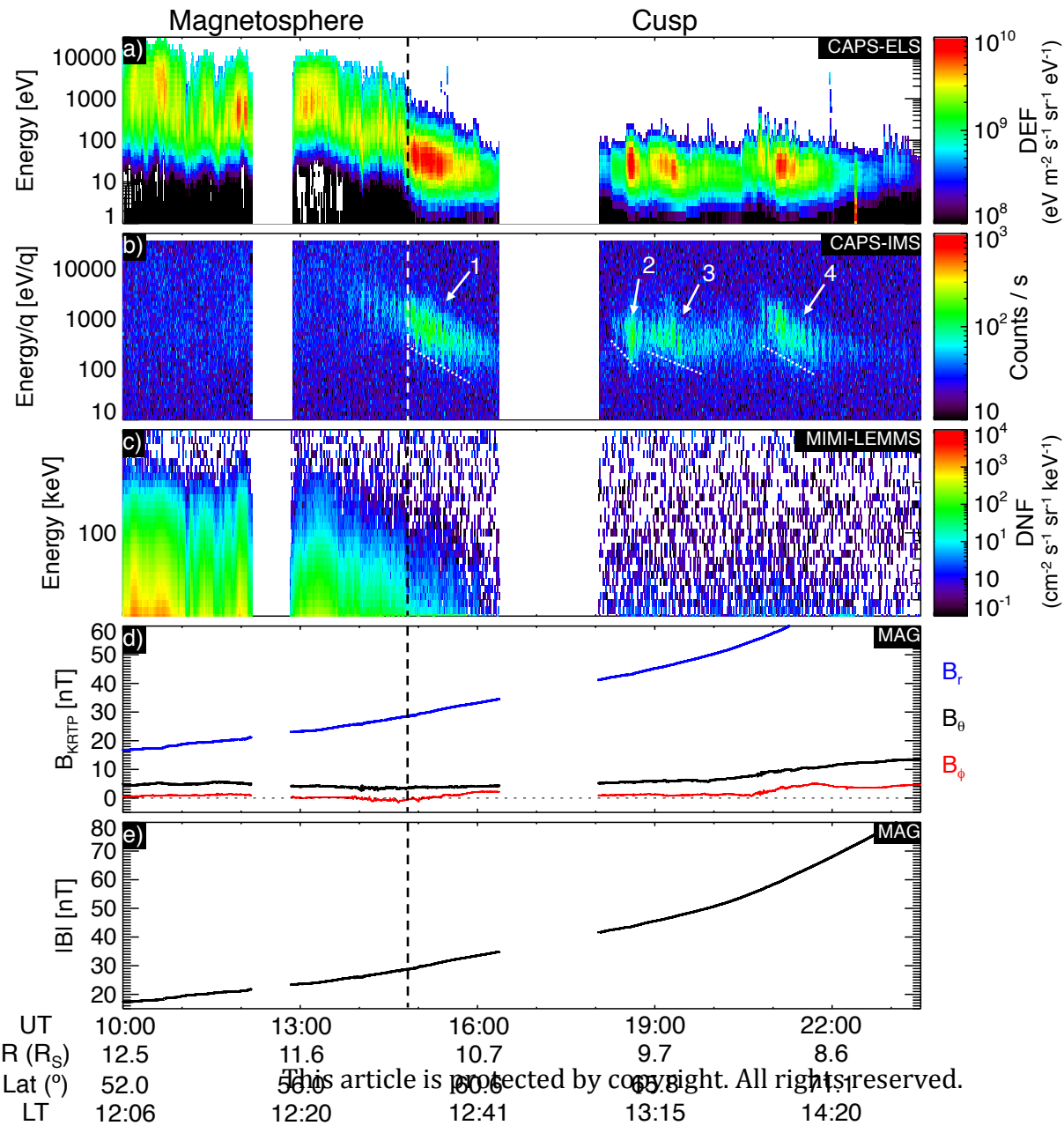
**Figure 7.** A projection of the estimated locations of reconnection from the calculated field-aligned distances (using the energy-pitch angle dispersions and the *Burch et al.*, [1982] model) are shown in red, and associated errors in blue. The plot is in the Y-Z KSM plane (viewed from the Sun) with the sunlit planet in the centre and an average model magnetopause location (dotted) also shown (calculated using the *Kanani et al.*, [2010] model and the compressed standoff distance value ( $22 R_S$ ) from the bimodal distribution found by *Achilleos et al.*, [2008]).

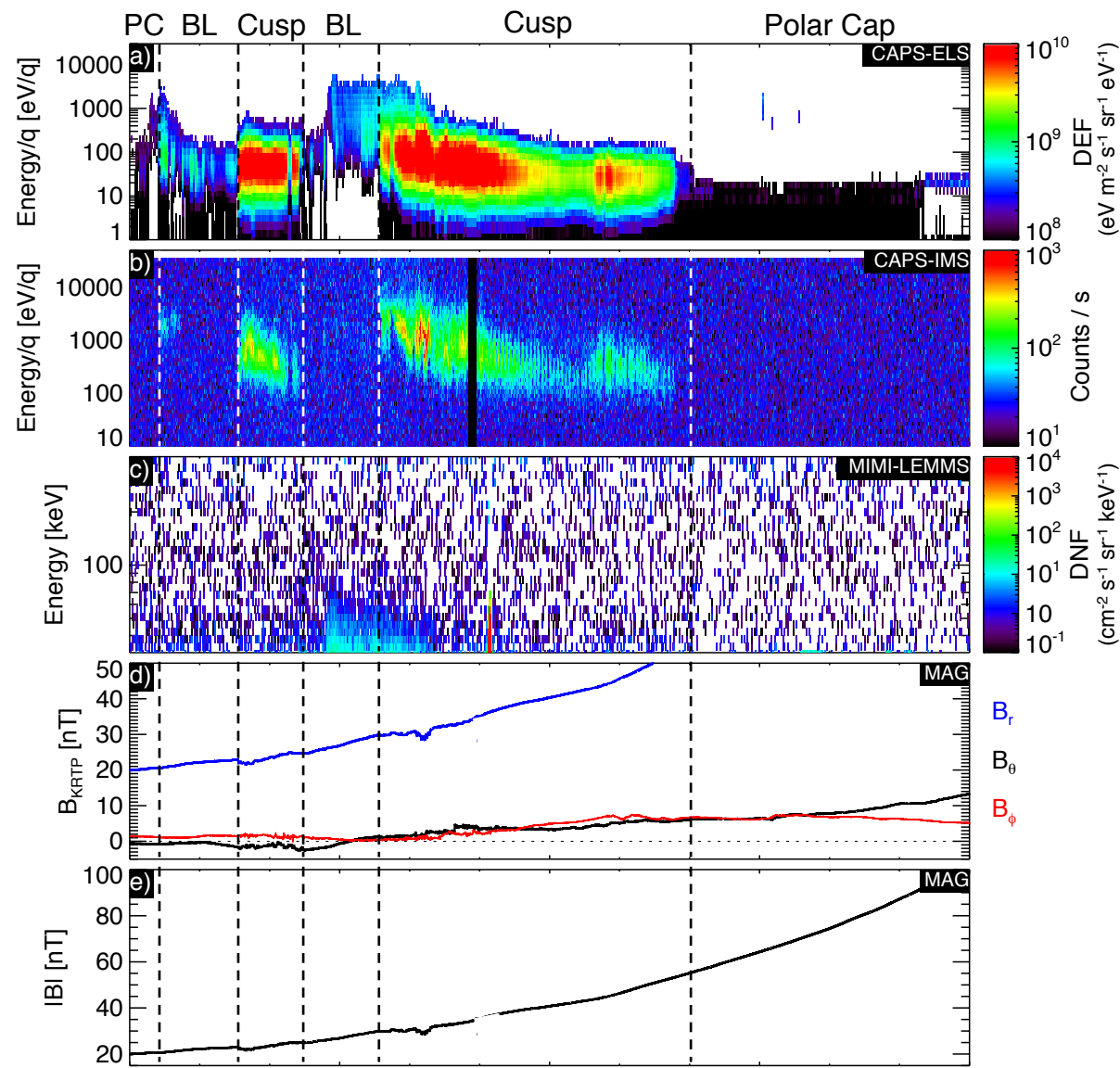
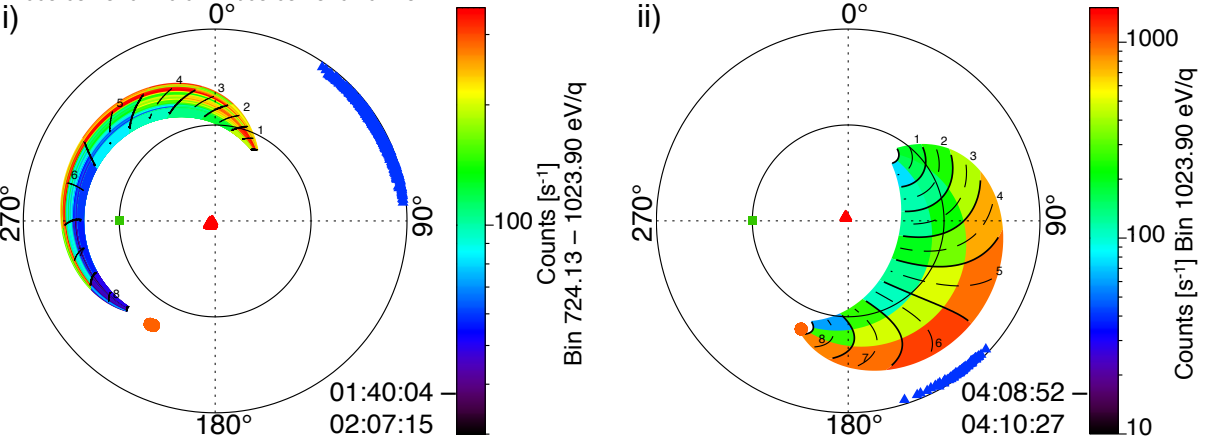
**Figure 8.** mSWiM propagations of the upstream solar wind conditions at Saturn for 10 days before and after the cusp observations (with an uncertainty of 15 hours). The ram pressure ( $P_{RAM}$ ) and the Alfvénic Mach number ( $M_A$ ) are presented in black and red, respectively. The number of days since apparent conjunction is shown in brackets next to each observation. The dashed line represents the start of the cusp observation. The day of year is labelled as ‘DOY’.

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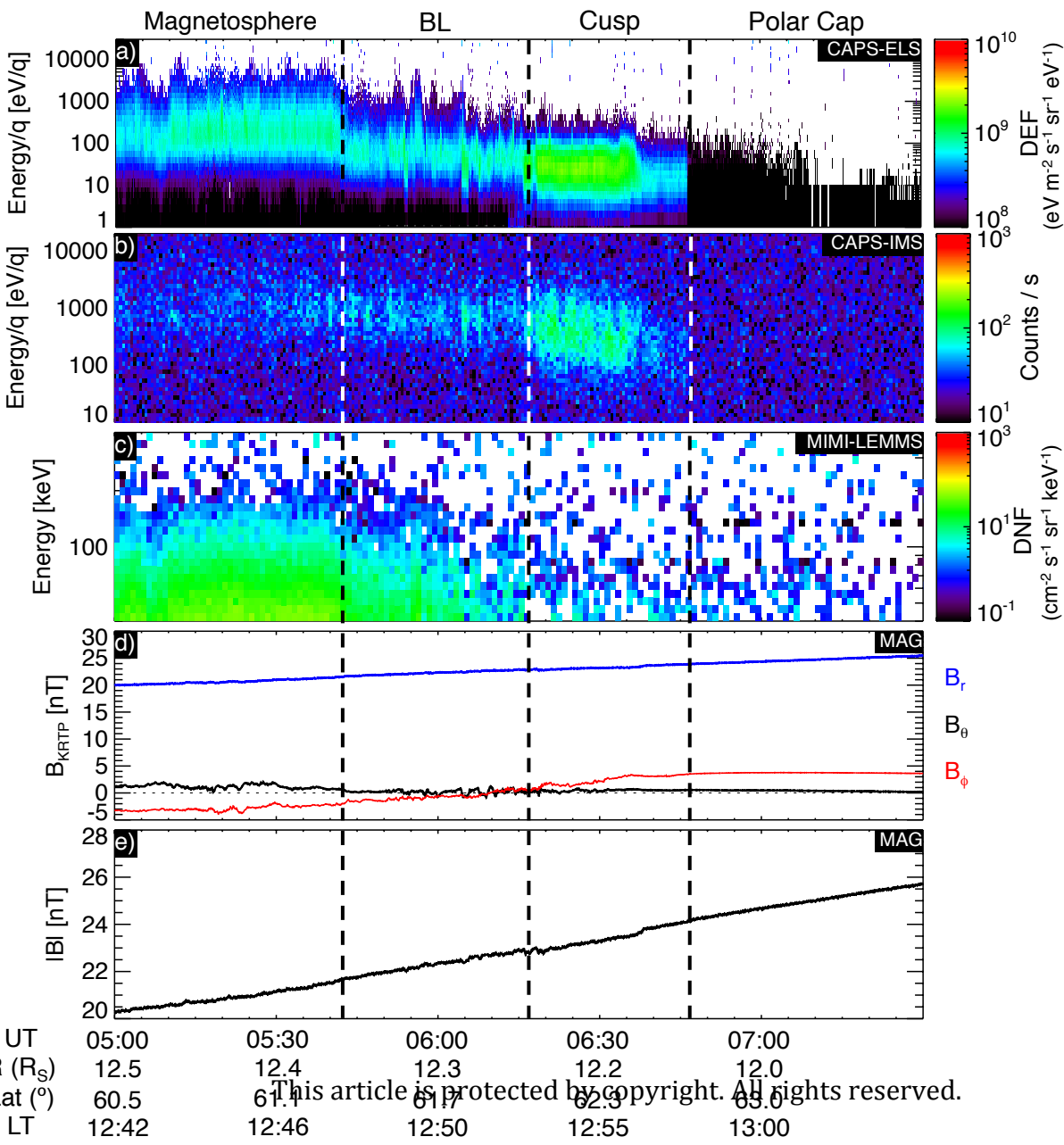




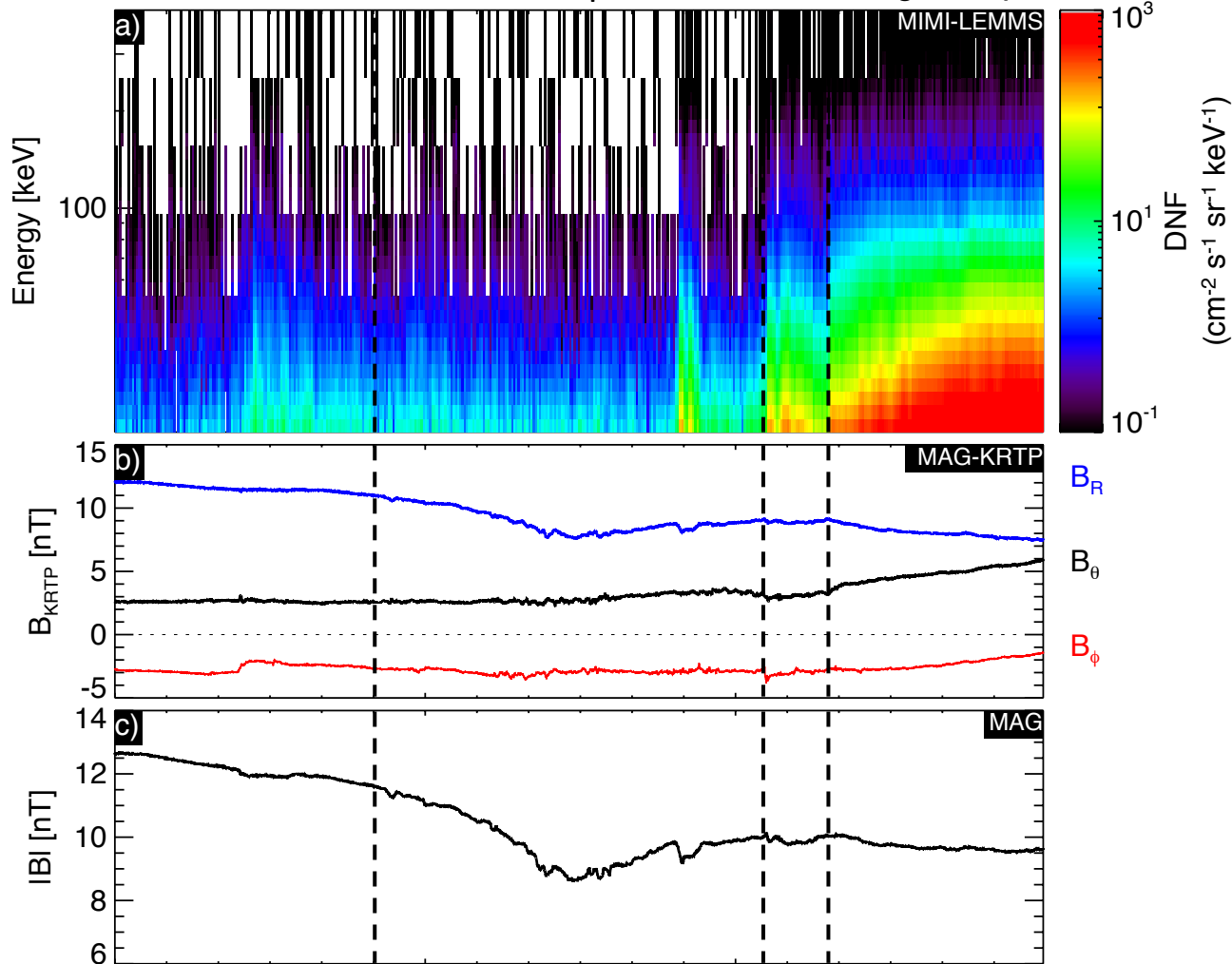


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R ( $R_S$ )	12.1	11.1	10.0	8.8	7.5
Lat ( $^\circ$ )	54.7	58.2	62.0	66.0	69.0
LT	13:06	13:27	13:58	14:50	16:21

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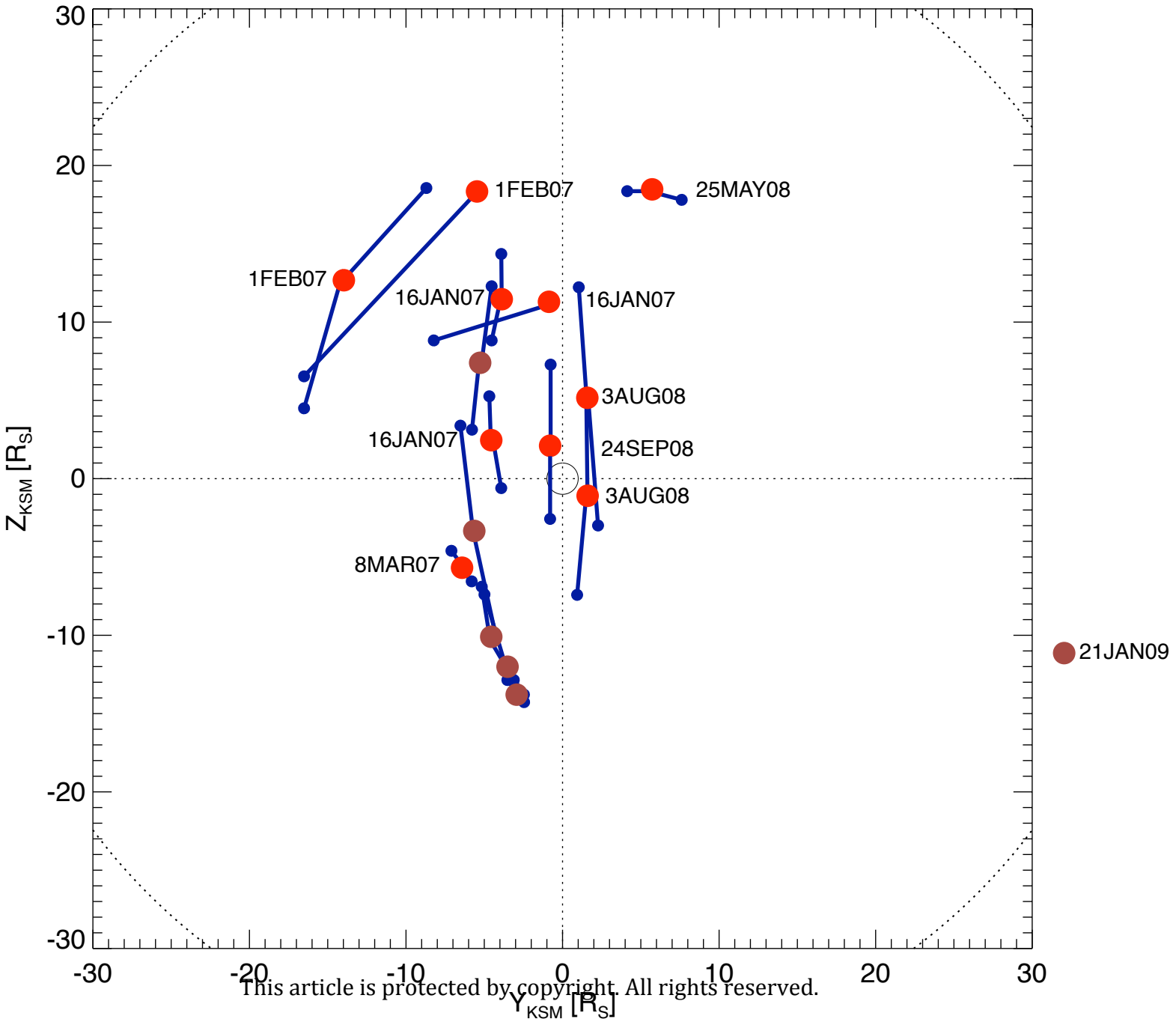
Cusp BL Magnetosphere



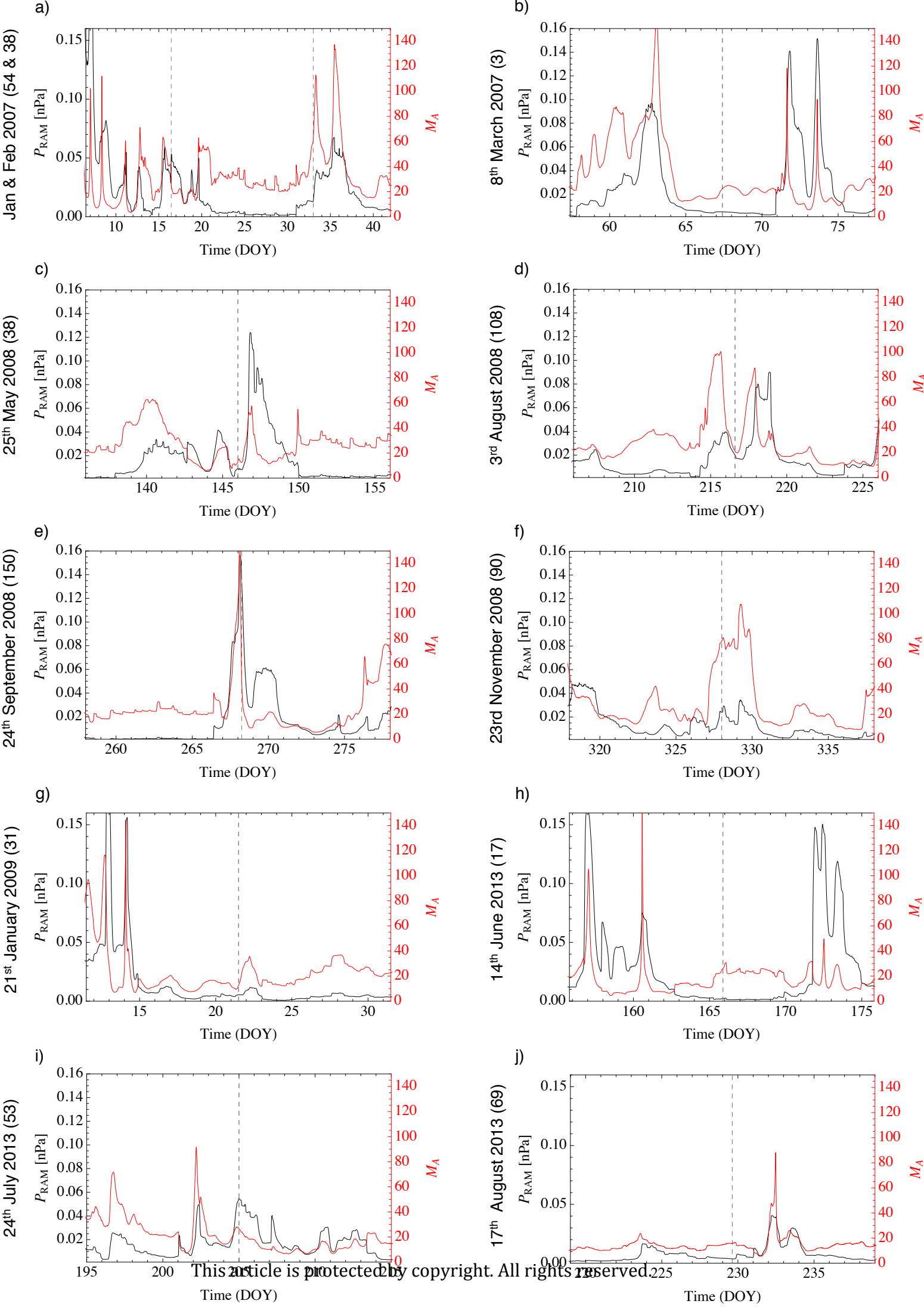
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 $R_S$  14.0  
 LAT ( $^\circ$ ) 42.2  
 LT 10:40

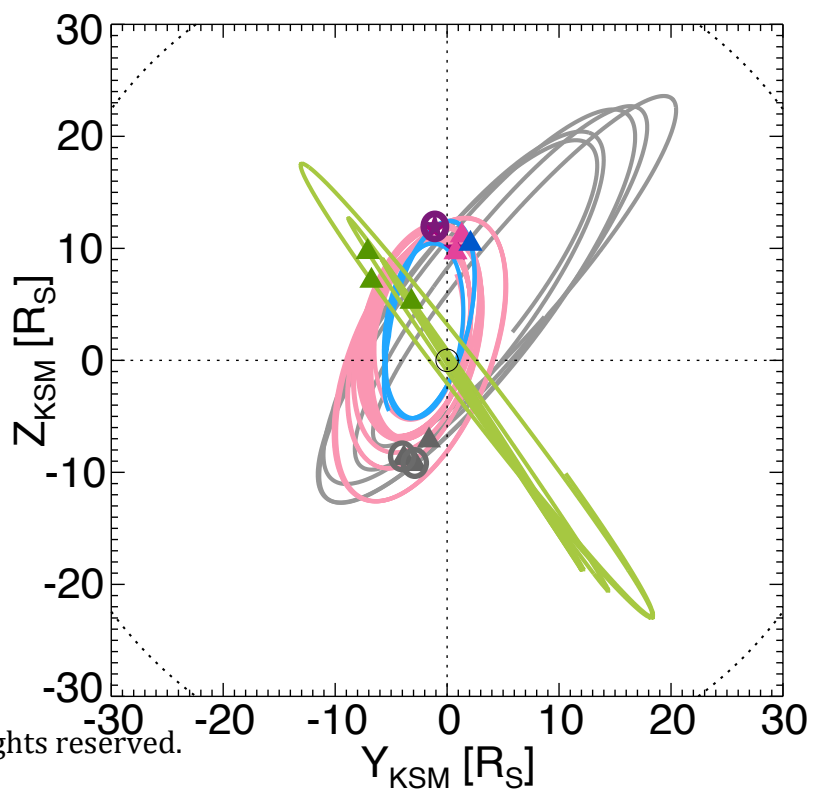
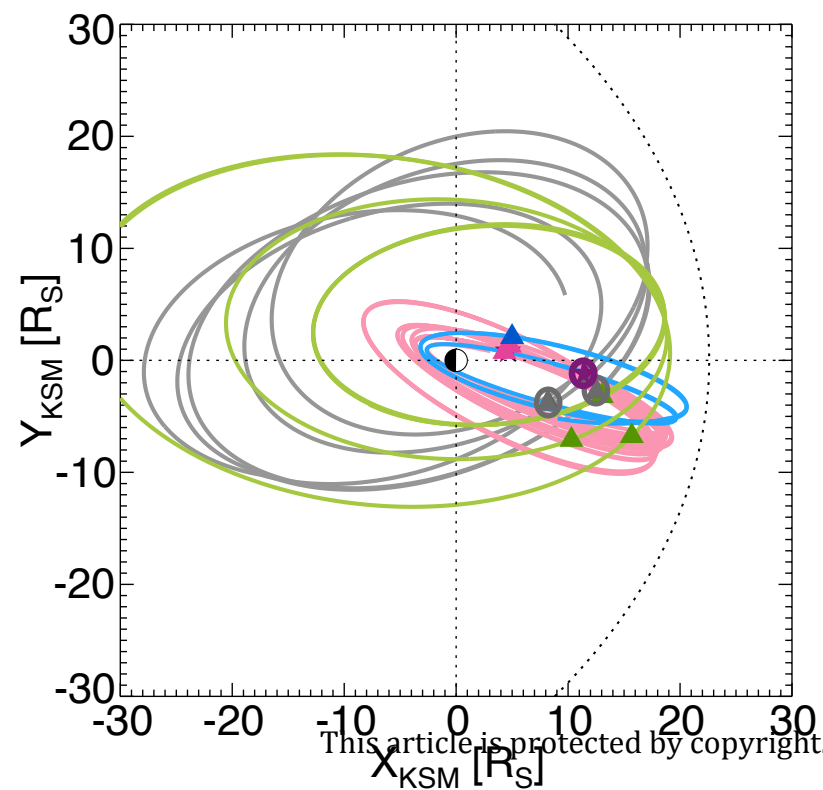
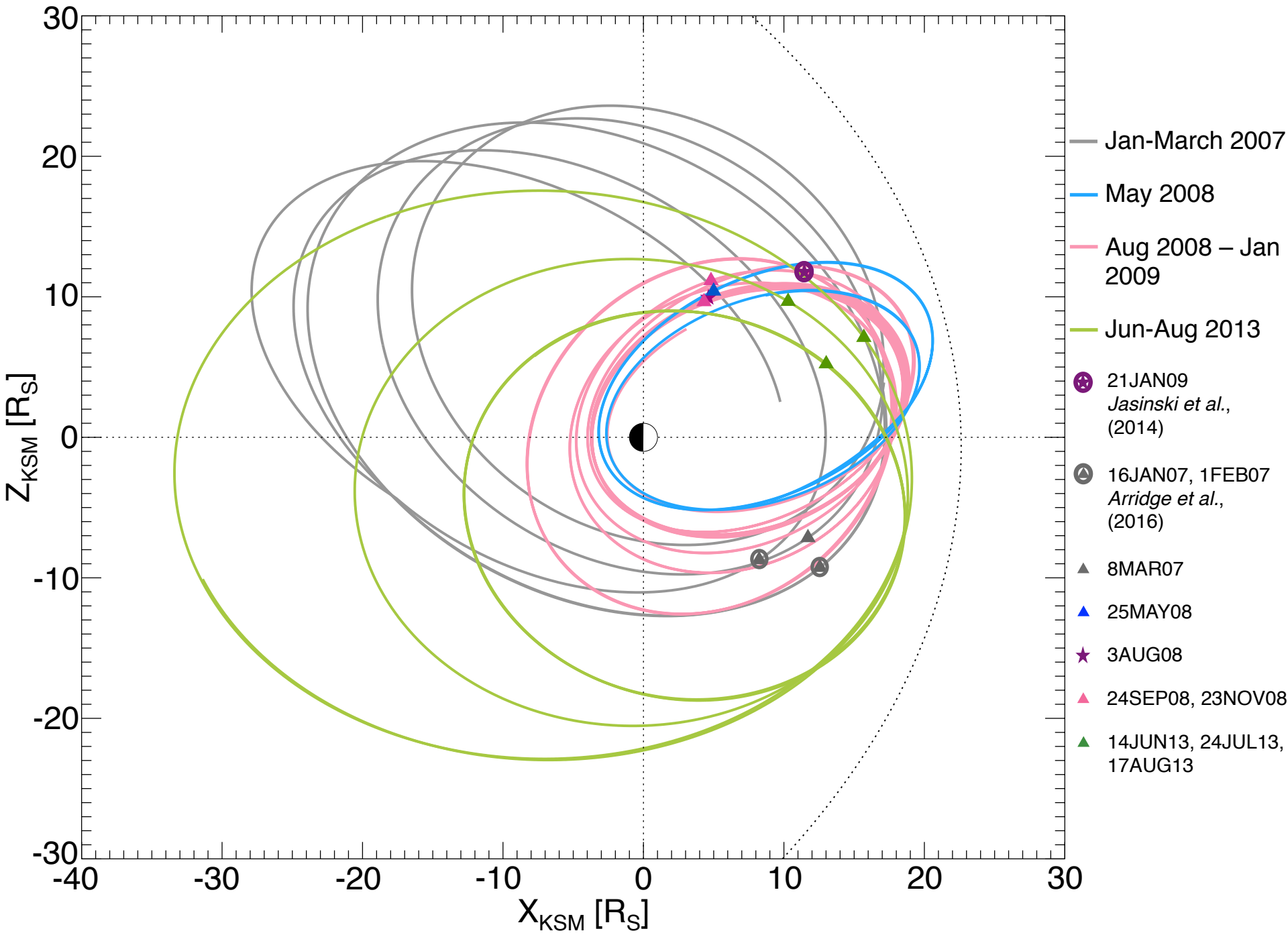
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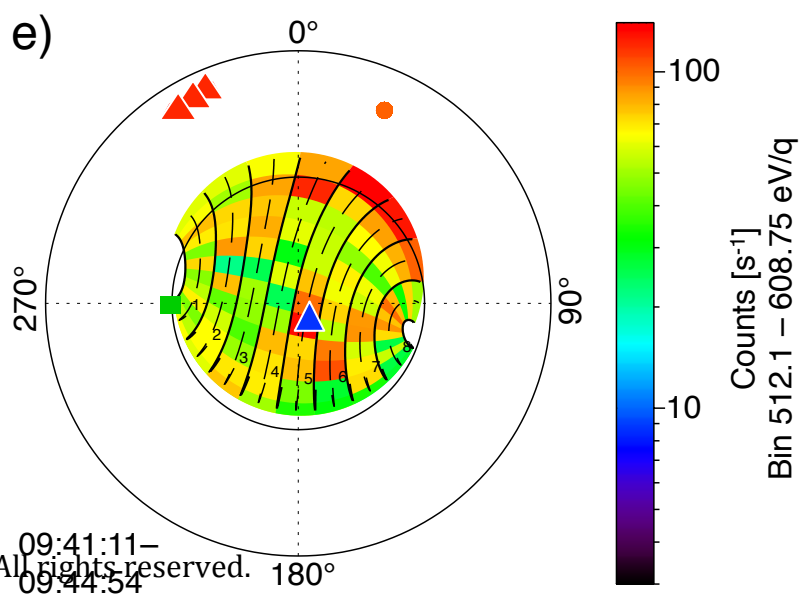
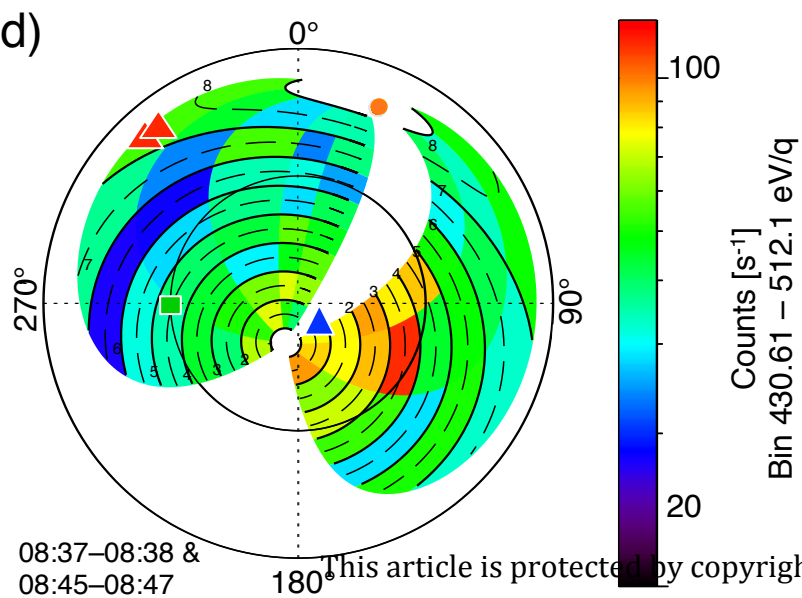
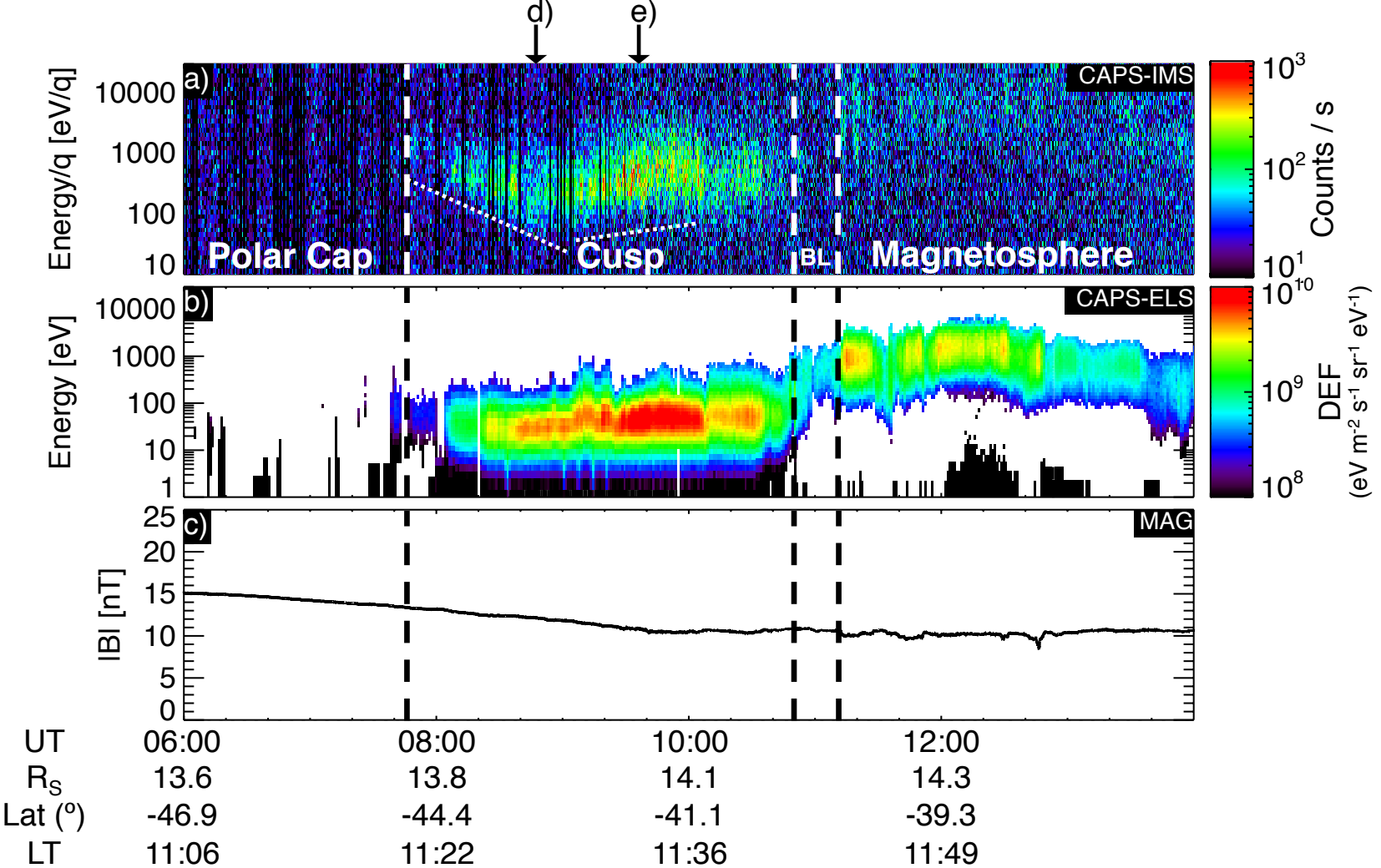
20:00 14.3 39.8  
 22:00 14.6 37.5  
 10:51 11:02

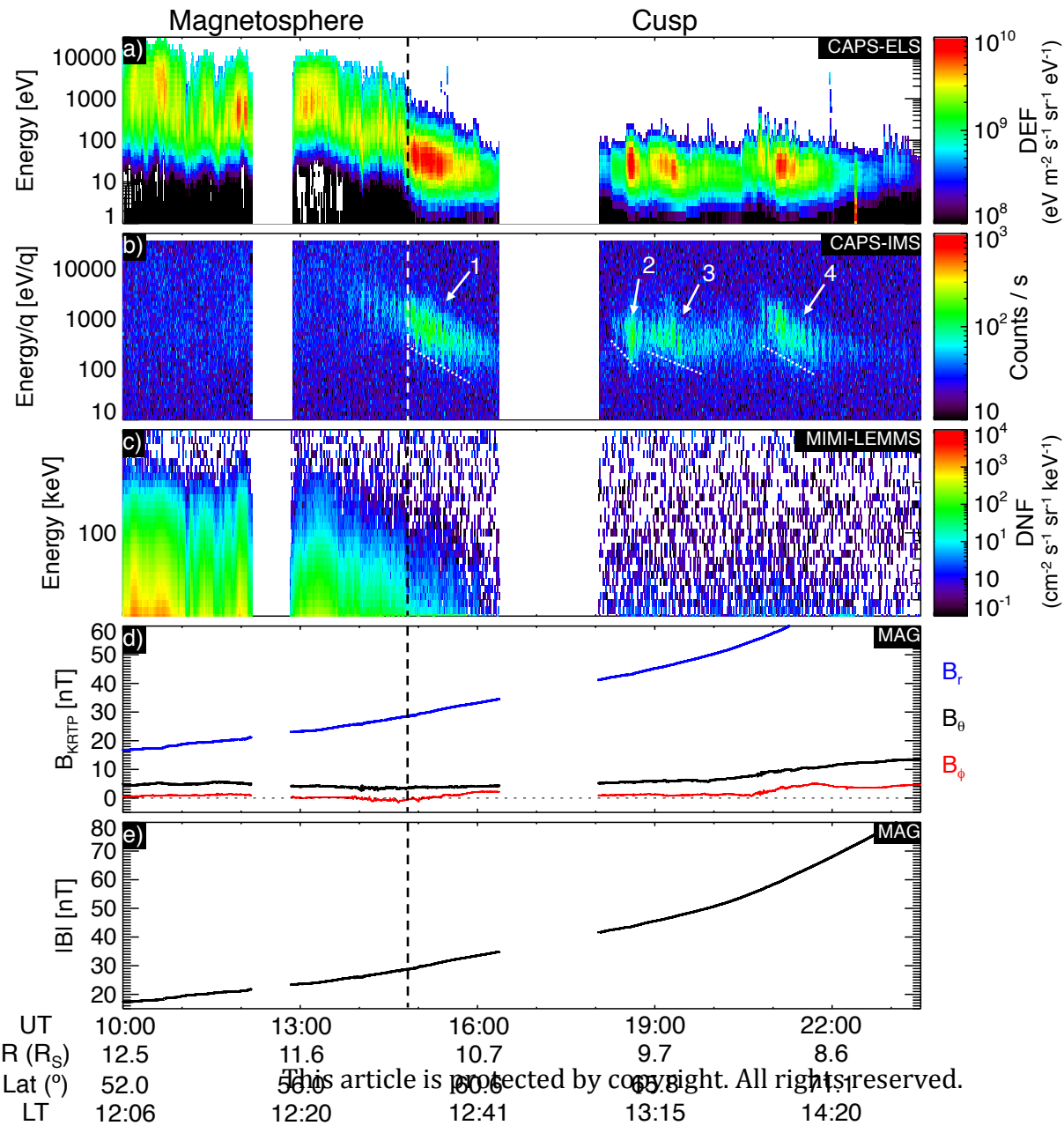


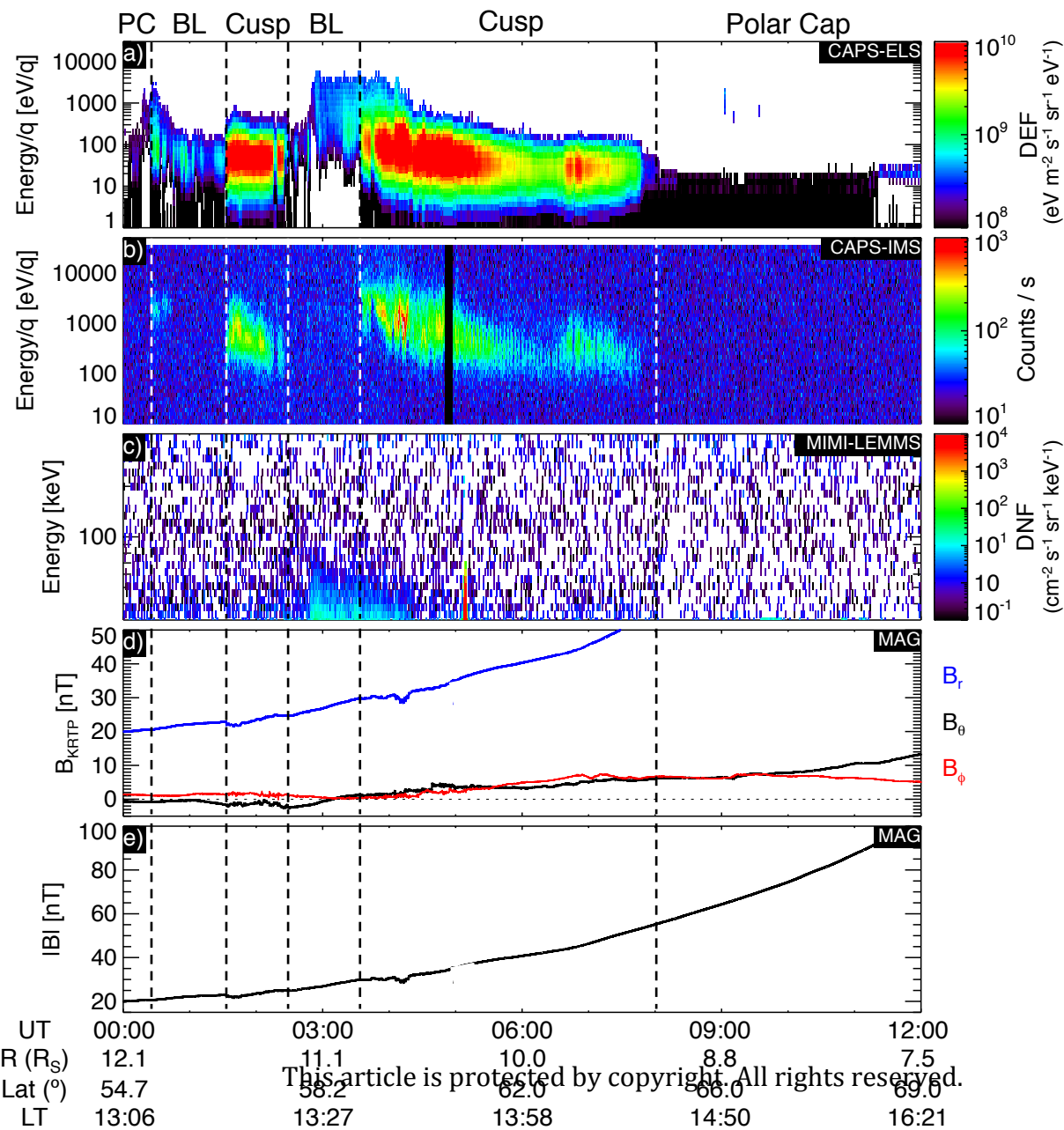
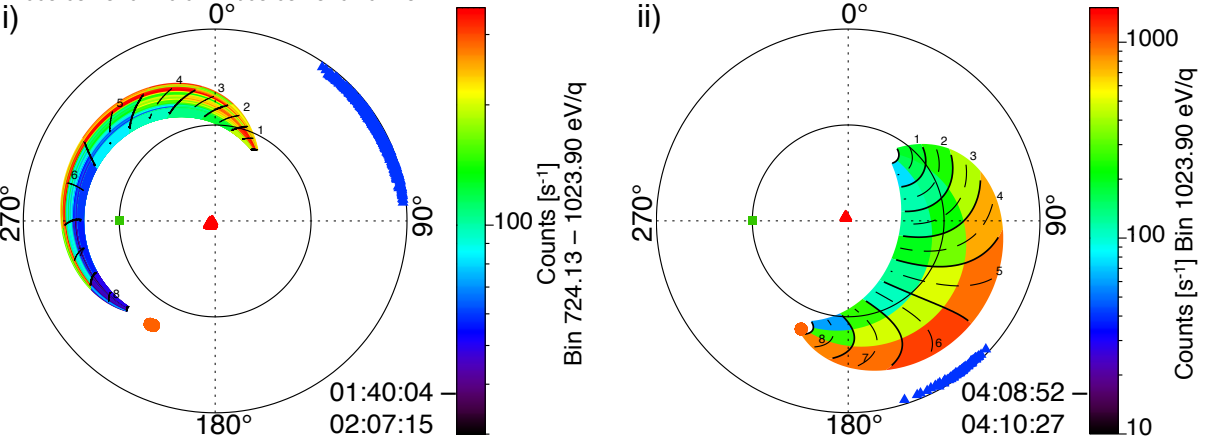


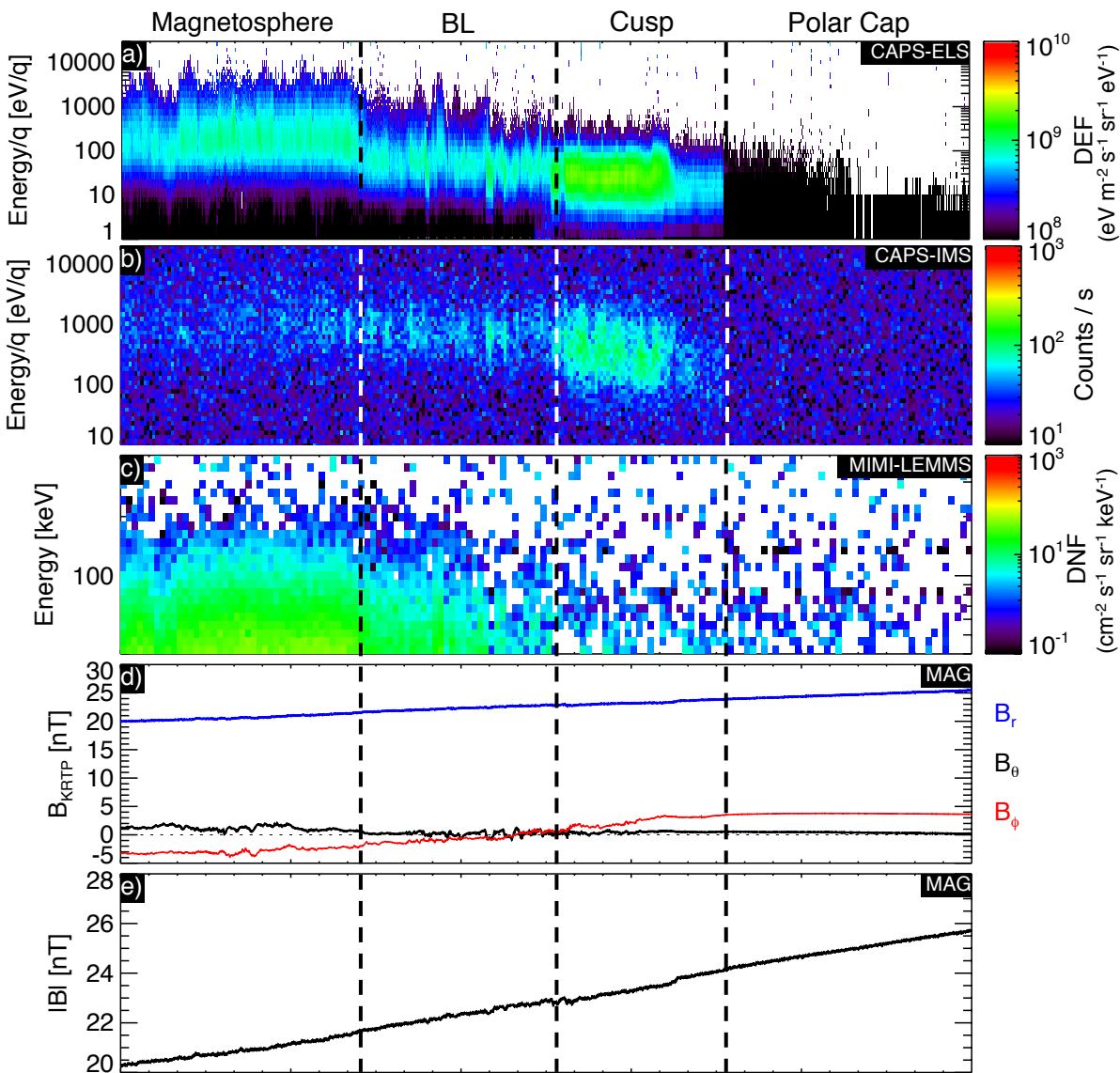






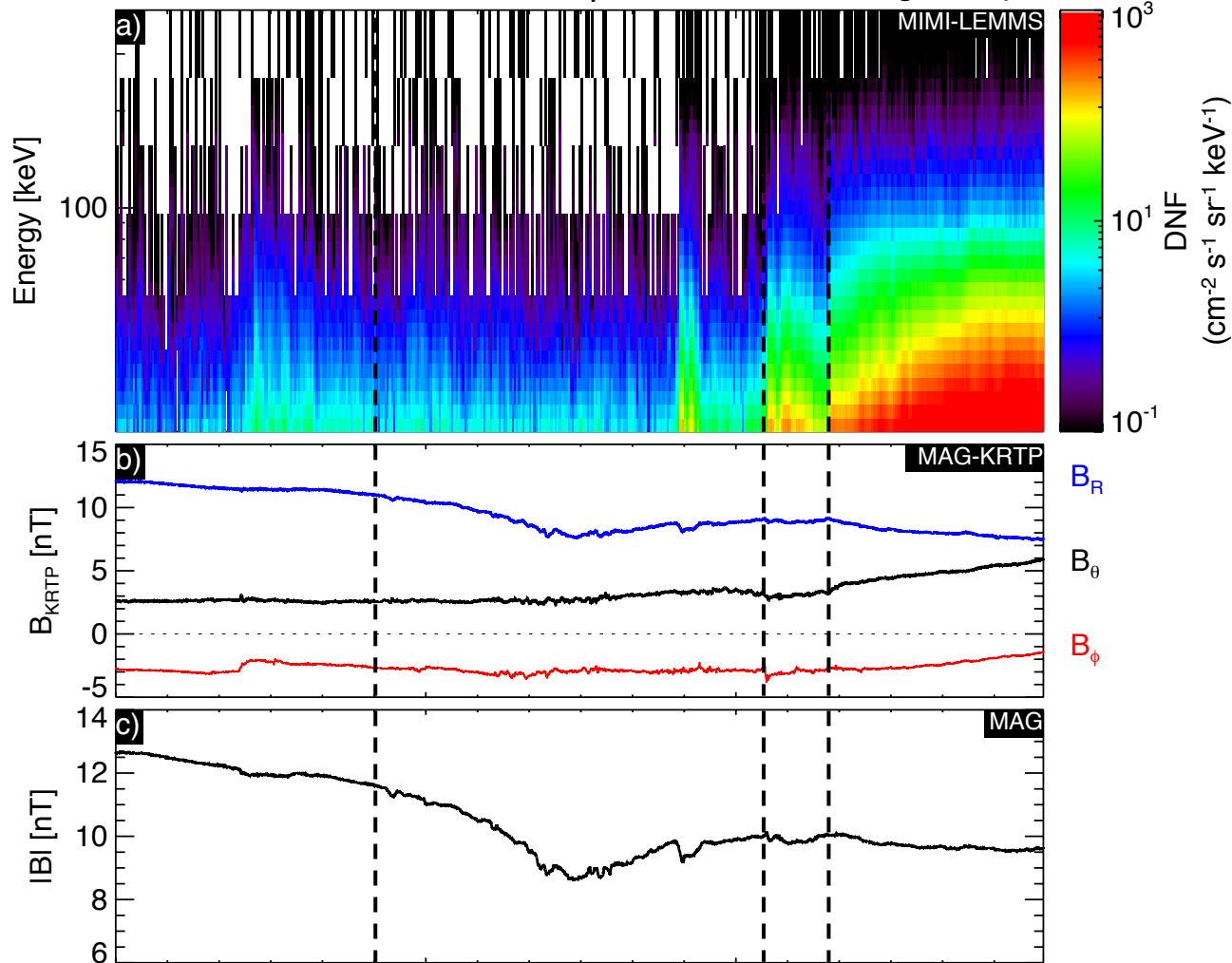






UT	05:00	05:30	06:00	06:30	07:00
R ( $R_S$ )	12.5	12.4	12.3	12.2	12.0
Lat ( $^\circ$ )	60.5	61.1	61.7	62.9	63.0
LT	12:42	12:46	12:50	12:55	13:00

Cusp BL Magnetosphere



UT	18:00	20:00	22:00
$R_S$	14.0	14.3	14.6
LAT ( $^\circ$ )	42.2	39.8	37.5
LT	10:40	10:51	11:02

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