

## Article

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# THEMIS observations and riometry: a data comparison with a view to proxy and prediction

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## Abstract

1  
2 A comparison has been made between radio absorption events observed by riometer at  
3 selected times of day and bursts of electrons observed in the midnight sector by THEMIS  
4 satellites. The correlation is found to be good for absorption in the noon and midnight sectors  
5 but poor around dawn and dusk. For noon and midnight the absorption can be estimated  
6 from the THEMIS electron flux to better than a factor of 2 in most cases. In the noon sector  
7 the absorption follows the THEMIS event by about 30 minutes on average (though with  
8 considerable variation from case to case), but by night the absorption precedes the electron  
9 flux by about 8 minutes on average. Thus, the flux at THEMIS can be predicted from the  
10 absorption in the night sector, the accuracy being better than a factor of 3 in most cases.  
11 The flux observed also depends on the location of the satellite, reducing with increasing  
12 distance down the tail. It is estimated that the source of the tail events observed in this  
13 study was at about  $6R_e$ , and comparisons are made with the established general pattern of  
14 the substorm in auroral absorption.

## 15 **1 Introduction**

16 Auroral radio absorption was first identified as a distinct phenomenon by Reid and Collins  
17 (1959), and early studies established its character as a sub-storm phenomenon, the absorption  
18 events being stronger and more frequent during periods of enhanced solar and geomagnetic  
19 disturbance (Holt et al., 1961). Its incidence in local time and magnetic latitude was first  
20 defined by Hartz et al. (1963), Driatsky (1966), and Hargreaves and Cowley (1967).

21 Jelly et al. (1964) and Parthasarathy et al. (1966) developed associations between the level of  
22 radio absorption and the incoming flux of electrons of energy greater than 40 keV observed by a  
23 low-orbit satellite, and later work based on incoherent-scatter radar has shown that the amount  
24 of absorption is consistent with the resulting increase of electron density in the lower ionosphere  
25 (Hargreaves and Devlin, 1990; Birch et al., 2013).

26 The above comparisons between electron flux and absorption used observations on satellites  
27 passing over, or close to, the site of the riometer used for the absorption measurement. However,  
28 in verifying auroral absorption as a substorm driven phenomenon, Parthasarathy and Reid (1967)  
29 showed that dayside absorption was also related to increased particle activity in the midnight  
30 sector, though with a time delay, and Hargreaves et al. (1968) verified this using data from Vela  
31 satellites some  $17 R_e$  down the magnetotail. It became clear from these studies that in a given  
32 absorption substorm the activity originated from the tail region on the night side of the Earth.

33 An objective of the present study is to explore these relationships in greater detail and to  
34 investigate whether the more recent observations of tail conditions using the Time History of  
35 Events and Macroscale Interactions during Substorms (THEMIS) group of satellites (Angelopoulos,  
36 2008) might enhance knowledge of these connections or even be useful in predictions.

## 37 **2 Observations**

38 The THEMIS satellites were launched in February 2007. A group of five, they were designed  
39 to study magnetotail phenomena and dynamics, particularly during substorms. Among the  
40 various sensors are the Electrostatic Analyser (ESA) and the Solid State Telescope (SST). The  
41 ESA covers the electron energy range from 7 eV to 31.2 keV, whereas the SST covers the electron  
42 energy range from 31 keV to 719.5 MeV. We shall use mainly the 41.0 keV and 93.0 keV SST  
43 energy channels in this study. The SST comprises two identical instruments per satellite, each  
44 instrument measuring electrons in two opposite directions thereby forming four reception cones

45 in all. Each satellite has a spin axis which is nearly orthogonal to the ecliptic plane and completes  
46 one revolution in about 3 seconds. The spin of the spacecraft, and the alignment and angular  
47 coverage of the reception cones, mean that the two SST instruments together provide almost  
48 omnidirectional measurement of the incoming electron flux, except for cones  $39^\circ$  wide centred  
49 on the vertical and an annulus  $13^\circ$  wide centred on the horizontal.

50 A 49-beam imaging riometer (IRIS), the Imaging Riometer for Ionospheric Studies (Browne  
51 et al., 1995), is used for the absorption measurements. Situated at Kilpisjärvi, Finland (ge-  
52 ographic latitude  $69.05^\circ\text{N}$ , longitude  $20.79^\circ\text{E}$ , L-value 5.9), it is slightly equatorward of the  
53 statistical maximum of the absorption zone. Our comparisons use only the vertical beam to  
54 determine the ionospheric radio absorption at the operating frequency of 38.2 MHz. Some refer-  
55 ence will also be made to observations by the European Incoherent Scatter (EISCAT) radar near  
56 Tromsø, Norway (geographic latitude  $69.9^\circ\text{N}$ , longitude  $19.23^\circ\text{E}$ , L-value 6.0), which is about  
57 112km north-west of IRIS.

### 58 **3 A comparison between THEMIS and IRIS peaks.**

#### 59 **3.1 Method of peak selection**

60 Comparisons with THEMIS satellite observations are restricted to periods when at least one  
61 spacecraft is between 2100 and 0300 LT and within  $3R_e$  of the ecliptic plane. (Though there  
62 was no range constraint down the magnetotail, all the observations were between  $5.5$  and  $16R_e$ ).  
63 Within these constraints, THEMIS passes through the tail were selected for four time sectors,  
64 specifically when IRIS was located in the midnight, dawn, noon and dusk sectors (22-24, 4-6,  
65 10-12 and 16-18 UT, or approximately  $23.5-1.5$ ,  $5.5-7.5$ ,  $11.5-13.5$  and  $17.5-19.5$  LT at Kilpisjärvi  
66 where the local time is 1.39 hours later than UT, and magnetic local time is 0.9 hours later than  
67 LT). The period from January to April 2008 was selected, a period when the satellites were  
68 predominantly in the tail region. This period includes an EISCAT radar run on 2008 March 9  
69 (see Section 5).

70 For each time sector, plots of the 41 keV flux observed at THEMIS were inspected visually,  
71 and events were selected for which the peak magnitude and time of occurrence could be clearly  
72 identified. The corresponding plots of the 38.2 MHz radio absorption at IRIS were then inspected  
73 for activity within about an hour of each THEMIS event. If present, the magnitude and time  
74 of the associated absorption events were noted. The approach to the data analysis is illustrated

75 by Figure 1 which shows a THEMIS-A event on 2008 February 15 with IRIS in the noon sector.  
76 The THEMIS-A flux peaked at  $487 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$  at 11:00 UT, and the absorption peaked  
77 at 0.4 dB at 11:21 UT. Not all the THEMIS passes were suitable for such a comparison, some  
78 being dominated by strong features of characteristic form, presumably due to the permanent  
79 Van Allen belts, and these were rejected from the data set.

### 80 **3.2 Basic statistics of the occurrence of associated features**

81 The initial data inspection identified 194 instances with at least one THEMIS satellite between  
82 2100 and 0300 LT within  $3R_e$  of the ecliptic plane. Of these, 62 were (or seemed likely to be)  
83 affected by the strong features mentioned above. Of the remaining 132 selections, 104 showed  
84 a measurable flux event at 41 keV, and inspection of the riometer data for those times showed  
85 a clearly associated absorption event of at least 0.1 dB on 66 days. Inspection of the list of  
86 substorm onsets identified from the SuperMAG electrojet (SME) index (Newell et al., 2011a,  
87 2011b) revealed that on all but 3 of the 66 days a magnetic substorm occurred within or close  
88 to the selected time period. Table 1 summarises these statistics in terms of the four selected  
89 IRIS sectors. For each comparison the event maxima (as seen in both the particle flux and  
90 the absorption) were noted, and also the times of these peaks. The observed electron densities  
91 indicate that in nearly all cases the satellite was in the plasma sheet when within  $10R_e$ .

92 Table 2 provides a more detailed summary of the data and shows the probability of the  
93 absorption being at least 1.0 and 0.3 dB over a selection of flux ranges in each of the four  
94 sectors. (On some days a flux event was observed by more than one satellite, and where that  
95 occurred all are included separately; Table 2 therefore shows more flux values in total (138) than  
96 Table 1 (104)). These results confirm that the relation between the two quantities is strongest  
97 for the noon and midnight sectors, as illustrated in Figure 2. For example, at noon, for a flux  
98 between  $100$  and  $330 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$  at 41 keV we expect a 6% chance of seeing at least 1.0  
99 dB absorption and a 69% chance of at least 0.3 dB. In no case (within our selection) was there  
100 an occurrence of more than 0.3 dB if the THEMIS flux remained below  $10 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$   
101 at 41 keV.

### 102 **3.3 Adjustment of flux for satellite position**

103 Figure 3 shows a mass plot of the observed flux and absorption values for the noon sector.  
104 Because of the difficulty of specifying very small values of absorption, those values less than 0.1

105 dB are indicated by diamonds. In many cases, an event was observed by more than one satellite  
 106 at different locations in the magnetotail, and where such multiple readings were obtained the  
 107 values are connected by horizontal lines. It is noted that there can be considerable variations  
 108 between these multiple values.

109 In order to determine whether these variations in flux may be due to differing locations  
 110 within the nightside region, variations of flux with satellite position were investigated. No  
 111 evidence was found for any systematic variation in the peak magnitude with the local time of  
 112 the satellite. However, there is a significant variation with the radial distance in the ecliptic  
 113 plane. This relationship was investigated using the 23 events which were observed by more than  
 114 one satellite in the nightside region (2100-0300 LT, and within  $3R_e$  of the ecliptic), all such  
 115 examples being shown in Figure 4a, in which the associated observations are connected. There  
 116 is clearly a tendency for the flux ( $F$ ) to reduce with increasing distance, suggesting a linear  
 117 relation of  $\log(F)$  as a function of  $r$  of the form  $\log F = c - kr$ ,  $r$  being the geocentric distance  
 118 in the ecliptic plane,  $k$  the gradient, and  $c$  a constant.

119 A value for  $k$  was determined using a cumulative minimising technique in which the difference  
 120 between each adjusted associated flux value was compared for a range of assumed values of  $k$   
 121 (Figure 4b). This suggests a value of  $k$  between 0.12 and 0.16; a value of 0.14 was therefore  
 122 assumed. To remove the influence of distance, the observed fluxes ( $F_r$ ) were therefore adjusted  
 123 to  $r = 10R_e$  ( $F_{10}$ ) using the formula -

$$\log\left(\frac{F_{10}}{F_r}\right) = 0.14(r - 10) \quad (1)$$

124 (A relationship of the form  $F_r \propto 1/r^3$  would also be a reasonable fit.)

125 In order to verify that the observed flux is related to the position of the satellite as well as  
 126 the strength of the associated absorption event, a partial correlation analysis was performed on  
 127 the data selections for the 22-24 UT and 10-12 UT periods. The analysis uses every observation  
 128 in the data set, not just those having simultaneous observations from 2 or more spacecraft.  
 129 The partial correlation coefficient is usually designated  $\rho_{12,3}$  where 1 and 2 are the quantities  
 130 correlated and 3 is the quantity "partialled-out" by the procedure.

131 The results of this analysis are summarised in Table 3, in which the observed flux is  $F$ , the  
 132 absorption is  $A$ , and the radial distance of the satellite is  $r$ . The significance of the correlation  
 133 coefficient is tested using Fisher's  $z$ -transform (Fisher, 1921; Moroney, 1951), the value of  $z$   
 134 being normally distributed with standard deviation  $1/\sqrt{N-3}$ ,  $N$  being the number of values.

135 By this means the probability ( $u$ ) of the correlation having arisen by chance may be estimated.  
136 The parameters  $z$  and  $u$  are included in Table 3, which verifies that the associations of  $F$  with  
137 both  $A$  and  $r$  are very significant, whereas there is no significant association between  $A$  and  $r$ .

### 138 **3.4 Detailed comparison of magnitudes.**

139 For comparison purposes, the observed flux is adjusted to  $10R_e$  using equation (1). The  
140 variation of peak absorption ( $A$ ) with the adjusted peak 41 keV electron flux ( $F_{10}$ ) is shown in  
141 Figure 5 for the four IRIS sectors. Because of their relative uncertainty, low absorption values  
142 ( $< 0.1$  dB) are marked with diamonds and are not included in the correlation computations.  
143 Correlation coefficients and other statistical quantities derived from these distributions are given  
144 in Table 4. There is a clear distinction in these properties between the sectors. In the noon  
145 and midnight sectors the correlation coefficients (0.74 and 0.73) are highly significant, and the  
146 probability that they arose by chance is very small. In those sectors the absorption could be  
147 predicted from the observed flux to within a factor of about 1.7 standard error. For the dawn  
148 and dusk sectors the situation is quite different, with a small negative correlation which is of low  
149 significance. These times are near the diurnal minima in the occurrence of auroral absorption  
150 events, whereas the noon and midnight sectors are near occurrence maxima (Hargreaves, 1969).

## 151 **4 Peak-to-peak timing**

### 152 **4.1 The delay time between THEMIS flux peaks at 41 keV and IRIS absorp-** 153 **tion peaks**

154 The peak-to-peak delays between the bursts at THEMIS and the associated IRIS events for  
155 the four time sectors (midnight, dawn, noon, and dusk) are summarised in Figure 6. In nearly all  
156 cases where a valid comparison could be made it is clear that in the noon sector the absorption  
157 followed the THEMIS event in nearly every case, the median time difference being 29 minutes  
158 (with quartiles at 13 and 39 minutes). However, in the midnight sector the IRIS event preceded  
159 that at THEMIS, with a median time difference of 8 minutes (with quartiles at 4 and 9 minutes).  
160 The time differences are not so systematic for the dawn and dusk sectors, which is perhaps not  
161 surprising given the lack of correlation between the magnitudes in those sectors. However, in  
162 the dawn sector the flux precedes the absorption in 70% of the observations and the median  
163 time difference is 20 minutes. The tendency for the flux to precede the absorption is probably

164 significant in this case also.

165 Adding together the midnight and noon median values predicts a typical delay of 37 minutes  
166 from the night to the day absorption events. This is similar to the night-day difference estimated  
167 from absorption observations at stations widely separated in longitude (e.g Hargreaves, 1967;  
168 Pudovkin et al., 1968). Notable is the fact that in the midnight sector the absorption event  
169 precedes the burst of energetic electrons detected by the THEMIS satellite. This suggests that  
170 the source is closer to the field lines through Kilpisjarvi (at  $L = 5.9$ ) than to those through  
171 the satellite. Figure 7 shows the satellite locations in relation to the nose of the field line ( $L =$   
172  $5.9$ ) from Kilpisjärvi for each of the midnight sector events. The only consistency is that the  
173 THEMIS event never precedes the absorption event observed at the ground, though they are  
174 simultaneous on two occasions. The source location may be variable, but this result suggests  
175 that it is usually close to 6 Earth radii. According to Liang et al. (2007) substorm dipolarisation  
176 tends to occur near the duskward edge of the magnetotail, with which Figure 7 appears to be  
177 consistent. At least half of the flux events plotted have the appearance of a spike, though several  
178 are more complex in structure.

179 If the observed absorption precedes the flux, riometer observations near local midnight may  
180 serve as a predictor of particle bursts in the tail. For the midnight sector, using the same  
181 approach as in Table 2, but with absorption as the primary selection variable, there are 24  
182 THEMIS observations unaffected by belt contamination when absorption was at least 0.1 dB,  
183 21 of which were associated with measurable flux. These selections are summarised in Table  
184 5. For a numerical prediction of the flux (at  $10R_e$ ) from the observed absorption the regression  
185 equation for  $F_{10}$  on  $A$  given in Table 4 should be valid. The standard error of estimate in this  
186 case would be a factor of about 2.5. (The overall variation of flux observed in the 22-24 UT  
187 sector was a factor of about 100.)

## 188 4.2 Time delay between satellites

189 The 23 cases when there were 2 or more THEMIS satellites in the selected tail region frequently  
190 show a pattern of activity which is similar in general character though with differences in detail.  
191 Figure 8 shows an example. For 16 such events, time differences for apparently similar, well-  
192 defined features were studied. However, these fail to show any consistency regarding the direction  
193 and speed of a presumed propagating event. This may be in part due to the time resolution of  
194 the observations (either 1.6 or 3.2 minutes). Out of 29 comparisons from the 16 events, 62% of



195 the time differences were no more than 3 minutes and only two were more than 6 minutes.

## 196 **5 Spectral characteristics**

197 D-region observations were made using the EISCAT radar on the morning of 2008 March 9  
198 (Birch et al, 2013). Some examples of the spectra derived from the electron-density profiles  
199 are illustrated in Figure 9, together with the spectra observed by THEMIS-D. It is clear that  
200 in the period from 0253 until 0638 UT there is reasonable agreement between the two spectral  
201 estimates, even though the satellite is separated by 10 to 15 Earth radii in distance and 6 to 10  
202 hours of local time from the estimated nose of the field line through the EISCAT radar. The  
203 gradient of the spectrum is almost constant during this period, the flux steadily decreasing with  
204 increasing energy. However, by 0736 UT the spectrum is beginning to harden, with a maximum  
205 appearing between 50 and 100 keV, and by 0816 UT the change is pronounced.

206 To examine this matter further, the ratio between the fluxes at 93.0 and 41.0 keV was taken  
207 as an indicator of the hardness of the spectrum. The values were taken at the peaks for each  
208 energy, not necessarily at exactly the same time. Mass plots of hardness against the local time  
209 at the satellite and against its geocentric distance show no clear trends, suggesting that the  
210 observed variation of intensity with range is not accompanied by any systematic variation of  
211 spectrum.

212 Figure 10 shows the time variation of hardness parameter from THEMIS-D and -E, and also  
213 the same parameter derived from the EISCAT data, for the times when there was sufficient  
214 precipitation for an estimate to be made. (THEMIS fluxes  $< 0.1 \text{ cm}^{-2}.\text{s}^{-1}.\text{sr}^{-1}.\text{eV}^{-1}$  were  
215 excluded from the spectral ratio computations, which resulted in the gaps in the plots.) As  
216 indicated by Figure 9 there is reasonable agreement between THEMIS and EISCAT in the early  
217 morning, but the ratios diverge after about 0700 UT, with the spectrum deduced from EISCAT  
218 hardening considerably towards noon, a change which is not present in the THEMIS data. These  
219 results are consistent with the tendency towards spectral hardening in the day sector reported by  
220 Hargreaves and Devlin (1990). A likely cause is acceleration by interaction with whistler-mode  
221 VLF waves as the energetic electrons move eastward under gradient-curvature drift (Horne et  
222 al., 2003).

## 223 6 Discussion

224 Previous studies using THEMIS have compared results with properties of luminous aurora  
225 (e.g. Gabrielse et al., 2009; Keiling et al., 2009; Mende et al., 2009; Nishimura, 2010; Pu et al.,  
226 2010; Xing et al., 2010; Zou et al., 2010; Liu et al., 2011). The energies used in the present work  
227 are considerably higher than those producing luminosity, and the comparison with auroral radio  
228 absorption is more appropriate at these energies.

229 That the particles causing auroral radio absorption on the night side of the Earth might  
230 be produced by the annihilation of magnetic field in the tail of the magnetosphere was first  
231 suggested by Axford et al. (1965), and Reid and Parthasarathy (1966) found examples where  
232 the pattern of particle flux on the IMP-1 satellite at  $28R_e$  agreed closely with the variation of  
233 radio absorption observed from the ground. Collis et al., (1984) showed that electron fluxes in  
234 the range 20-160 keV at geosynchronous orbit ( $6.6R_e$ ) could be predicted from riometer data to  
235 an accuracy of 50% for the larger absorption events ( $>2\text{dB}$ ), the samples being taken from the  
236 whole day. More recently, Spanswick et al. (2007) have observed a close relation between rapid-  
237 onset events (spikes excluded) seen with the CRESS satellite at  $8R_e$  in the tail and absorption  
238 at  $L = 6.6$  observed by riometers near midnight in the Canadian sector. Clilverd et al. (2012)  
239 and Ovalle et al. (2012) have made comparisons between riometers in the Antarctic and fluxes  
240 observed by THEMIS in the tail, finding some clear associations between flux and absorption.  
241 According to riometer studies, the latitude of maximum absorption occurrence is at about  $67^\circ$   
242 magnetic latitude ( $L = 6.5$ ) during the period around midnight and into the morning, though  
243 before about 2100 LT the maximum is more poleward at  $72^\circ$  or beyond (Hargreaves and Cowley,  
244 1967). There is, however, considerable variation from case to case.

245 The timing of absorption events at the ground is also variable. As a rule they are seen  
246 first at about  $L = 5$  (magnetic latitude  $63^\circ$ ), from whence they spread both poleward and  
247 equatorward (Hargreaves et al., 1975). The latitude of the onset depends somewhat on the level  
248 of geomagnetic activity as indicated by  $K_p$ , there being some equatorward displacement if  $K_p$   
249 is large. The progression of absorption from the night to the day side has been noted on many  
250 occasions. There seems little doubt that the trapped electrons move eastward by the process  
251 of gradient-curvature drift in the terrestrial magnetic field (e.g. Horne et al., 2003). However,  
252 since the movement of structural features in the precipitated flux is eastward after midnight but  
253 westward before that, some other factor must be involved in the precipitation process, perhaps  
254 a propagating hydrodynamic wave (Hargreaves, 1968). This is still an open question, however.

255 A previous comparison between  $\geq 45$  keV electron flux observed at  $17 R_e$  by Vela satellites  
256 in the tail and auroral absorption at a number of riometers in the auroral zone (Hargreaves et  
257 al., 1968) found that the absorption event at  $L = 7$  in the midnight sector generally precedes the  
258 increase of flux at Vela by 20 to 30 minutes, implying an outward motion. It was suggested that  
259 the field lines reaching  $17 R_e$  typically connect to the ground at about  $L = 14$  ( $74^\circ$  invariant  
260 latitude). It was also estimated that the flux of energetic electrons entering the atmosphere was  
261 considerably greater than the associated flux at  $17 R_e$ .

262 In many cases a weak bay-like event, the "pre-onset bay", is observed before the main event.  
263 These can be extensive in longitude, and are first seen at a relatively high latitude, from which  
264 they drift equatorward within the range  $L = 16$  to 4, with most individual cases covering between  
265 one and five or six units of  $L$ . The median speed over the ground is 100-200 m/s. It was suggested  
266 (Hargreaves et al., 1975; Ranta et al., 1981) that this motion may be due to ExB drift of plasma  
267 in the magnetotail under the influence of the cross-tail electric field. The main event often  
268 appears first near the eastern end of the bay, which would generally be in the midnight sector.

269 The "spike event" is another absorption feature that may be significant. This is of short  
270 duration and often marks the beginning of an absorption substorm as seen on the nightside of  
271 the Earth. Spike events generally, though not always, move poleward, though there can also be  
272 an east-west component. In the European sector, which includes Kilpisjärvi, the speeds are in  
273 the range 200-3000 m/s over the ground (Ranta et al., 1981; Hargreaves et al., 1997; Ranta et  
274 al., 1999). Taken together, these observed absorption features constitute the so-called "reversed-  
275 y" event (Hargreaves et al., 1975). Features of spikey appearance were present in many of the  
276 THEMIS events studied.

277 Recent observations by satellites in the tail, in some cases compared with ground-based  
278 observations, have produced a range of ideas about processes and their locations, some at or  
279 even beyond 25 Earth radii, others in the so-called "near-Earth" region at about 7-10 Earth radii  
280 (Petrukovich and Yahnin, 2006; Lui, 2007; Xing et al., 2010). The present comparison between  
281 auroral absorption features near midnight and energetic particle bursts in the tail, in which  
282 the absorption event seen at about 6 Earth radii always precedes the THEMIS event, clearly  
283 supports a near-Earth source for the main substorm event. However, the studies of pre-onset  
284 absorption activity indicate that the onset is preceded by the inward movement of a feature  
285 from a much greater distance, whose arrival closer to the Earth then triggers the main event.  
286 The existence of two apparent sources of energetic particles was pointed out by Ashour-Abdalla

287 et al. (2011), the first one at a reconnection region producing particles of relatively low energy,  
288 and a subsequent one producing particles of higher energy due to dipolarisation of the magnetic  
289 field closer to the Earth. The implication of separate low- and high-energy fluxes produced at  
290 different times and different locations within the magnetotail would appear to be consistent with  
291 the pattern of auroral absorption and apparent sources as described above.

## 292 7 Summary

293 There is a significant association between the 41 keV electron flux observed by THEMIS in  
294 the magnetotail and the auroral radio absorption at 38.2 MHz at Kilpisjärvi in the noon and  
295 midnight sectors. The association is much weaker in the morning and evening sectors.

296 The electron flux also depends on the location, falling off exponentially in proportion to the  
297 distance down the tail.

298 At noon and midnight the absorption could serve as a proxy for the tail flux within a factor  
299 of 2 in most cases.

300 The tail flux usually precedes the absorption at noon but follows the absorption at midnight,  
301 the median times being 29 and 8 minutes respectively, though there can be considerable variation  
302 from case to case. The tail flux could therefore serve as a predictor of noon absorption, and  
303 the midnight absorption as a predictor of tail flux. In the latter case the magnitude would be  
304 predicted to an accuracy better than a factor of 3 in most cases.

305 The relative timing in the midnight sector suggests outward movement of the flux event  
306 down the tail from a source close to  $6R_e$ .

307 A comparison with spectra derived from incoherent scatter radar observations shows rea-  
308 sonable agreement between the spectra from THEMIS in the tail and the radar when in the  
309 post-midnight to early morning sector. Thereafter the spectrum of precipitating electrons hard-  
310 ens relative to the THEMIS measurement. No evidence was found for any systematic variation  
311 of spectral hardness with location in the tail.

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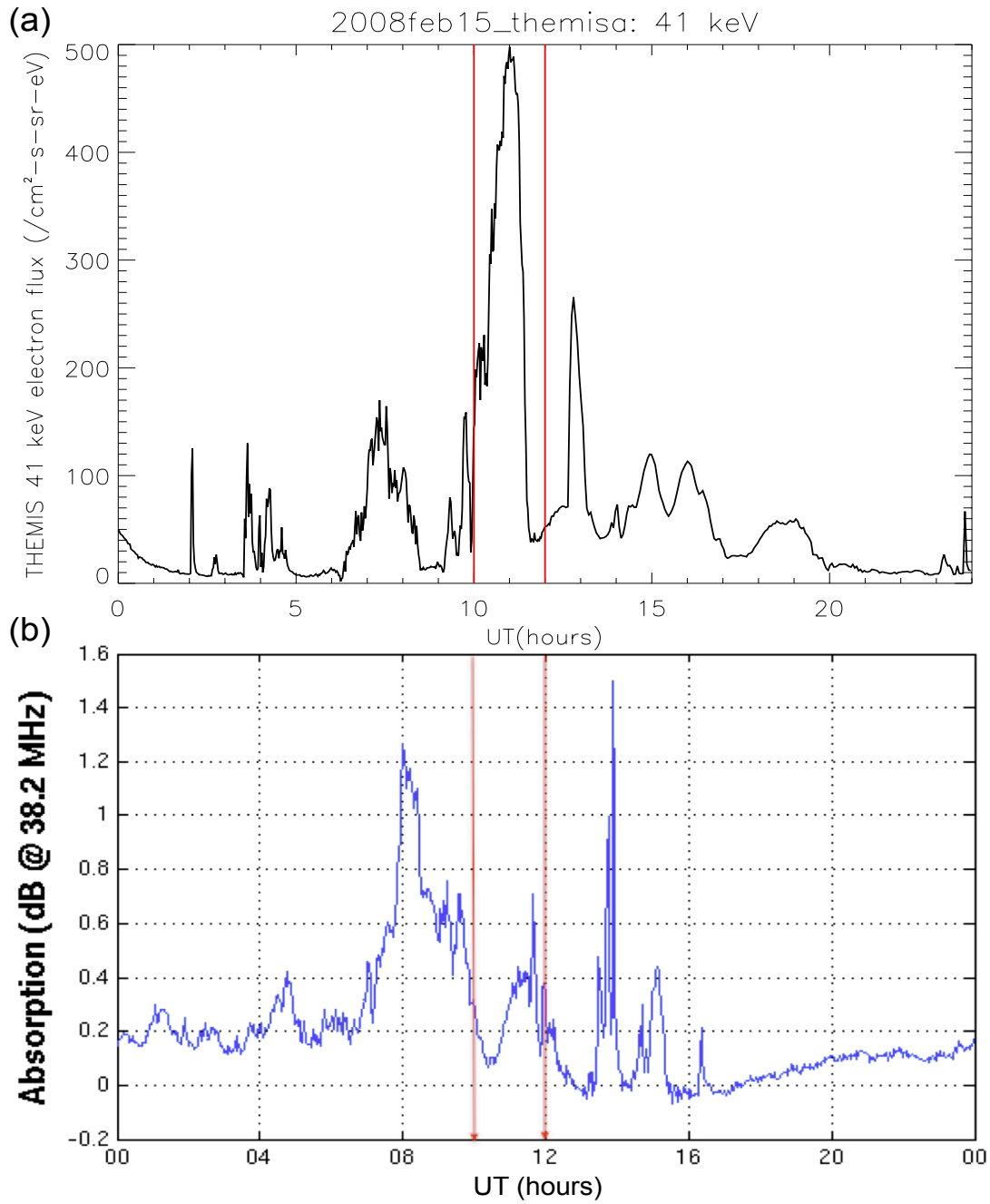


Figure 1: (a) THEMIS-A 41 keV electron flux ( $\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}\cdot\text{eV}^{-1}$ ) and (b) IRIS absorption (dB) on 2008 February 15. (Local noon at Kilpisjärvi is at 10.6 UT.)

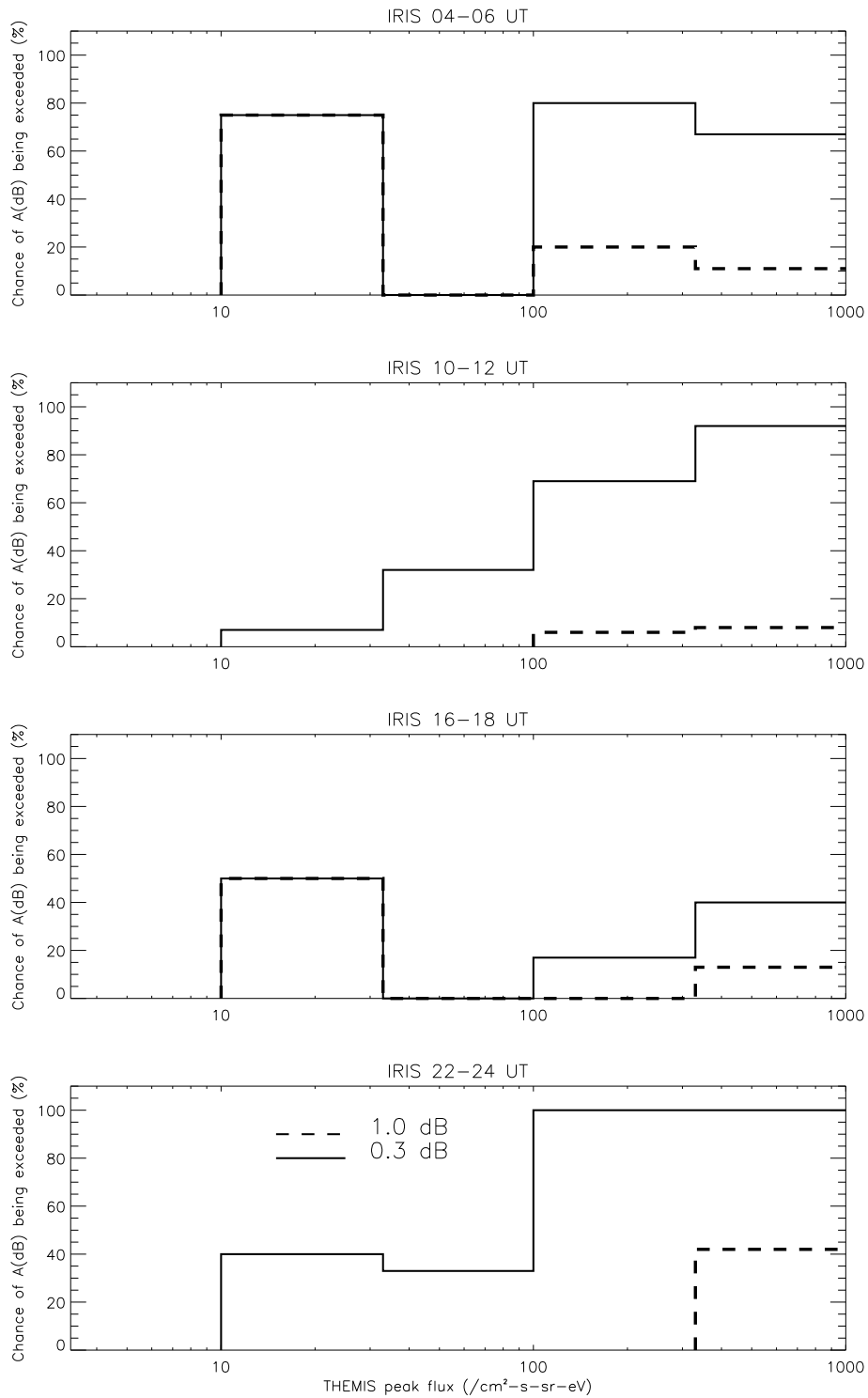


Figure 2: Probabilities of at least 0.3 dB and 1.0 dB in each of the four sectors for given ranges of 41 keV THEMIS flux

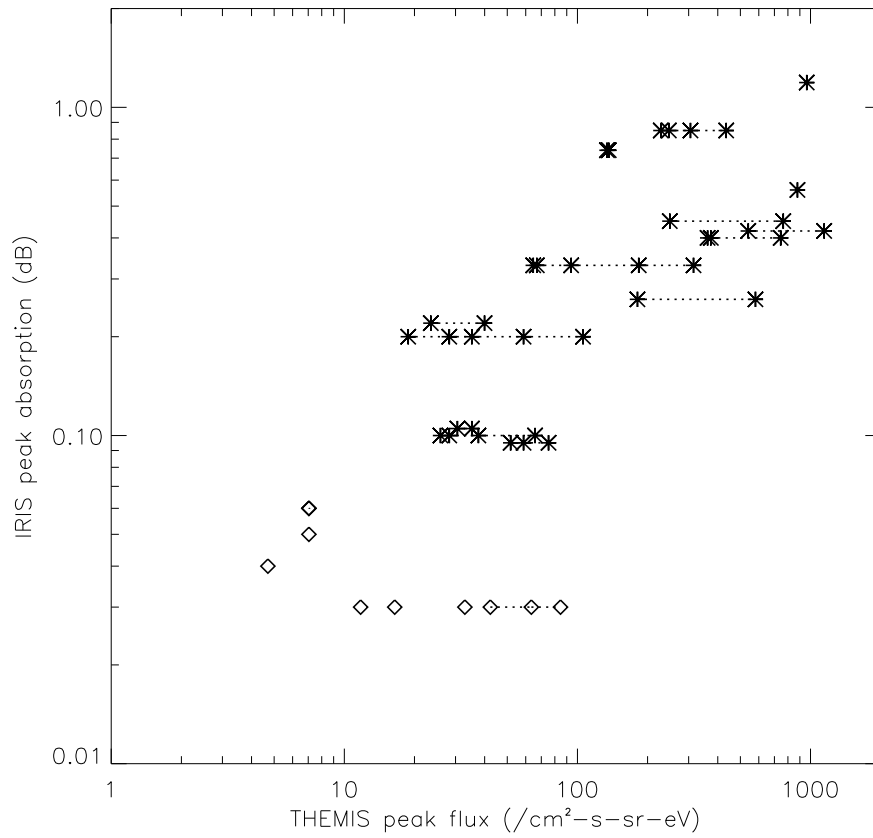


Figure 3: Peak absorption ( $A$  dB) against 41 keV peak flux ( $F \text{ cm}^{-2}.\text{s}^{-1}.\text{sr}^{-1}\text{eV}^{-1}$ ) for all measurable values from the set of 42 days in the IRIS noon sector. (Groups of points at 0.1 dB have been offset in absorption, for clarity; values  $<0.1$  dB are indicated by diamonds)

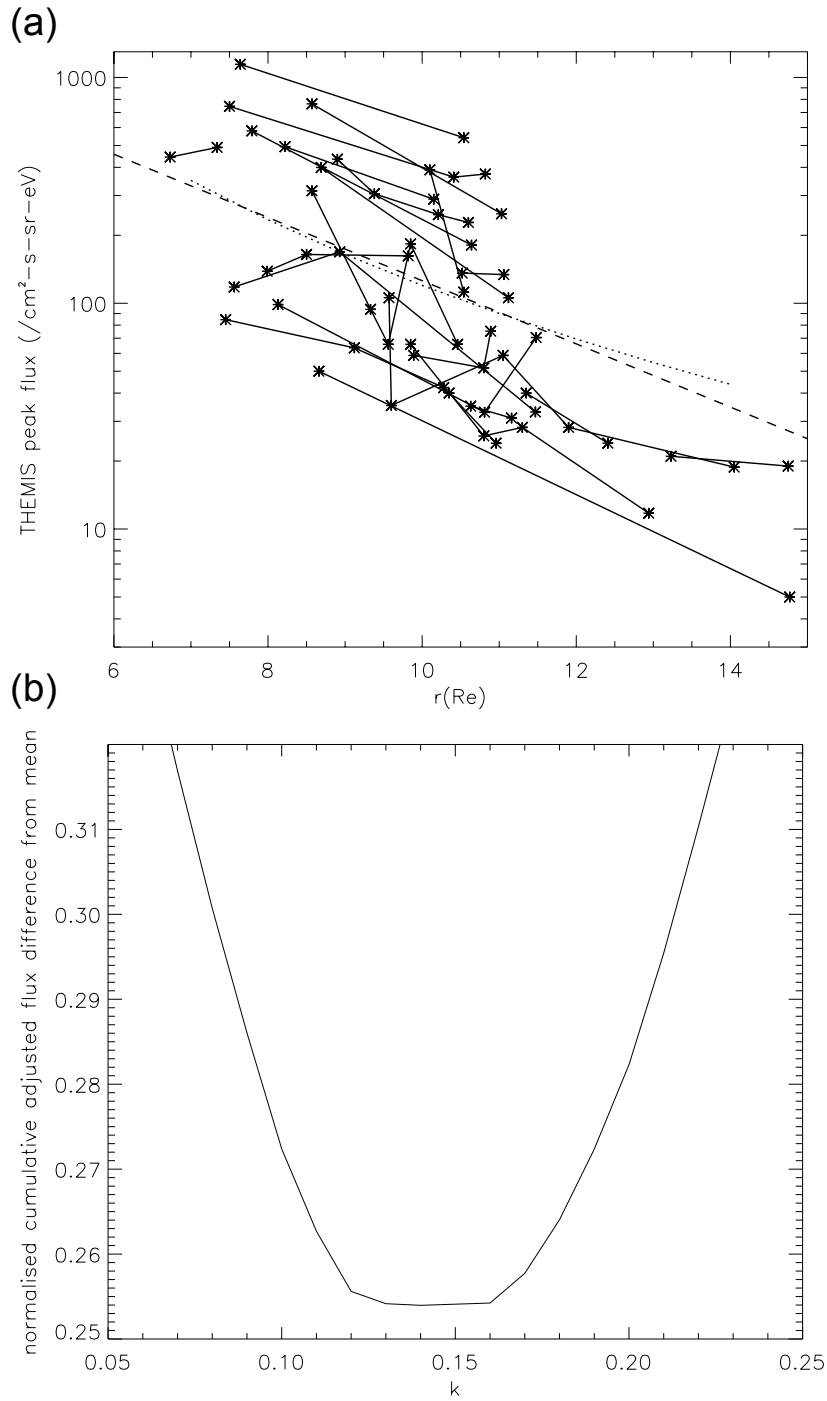


Figure 4: (a) Variation of 41 keV flux with geocentric radial distance in the ecliptic plane for the 23 events observed by 2 or more satellites. (The dashed line has gradient  $k = -0.14$ ; the dotted line represents the relation  $F \propto r^{-3}$ .) (b) Variation of "normalised cumulative adjusted flux difference from the mean" against gradient  $k$ .

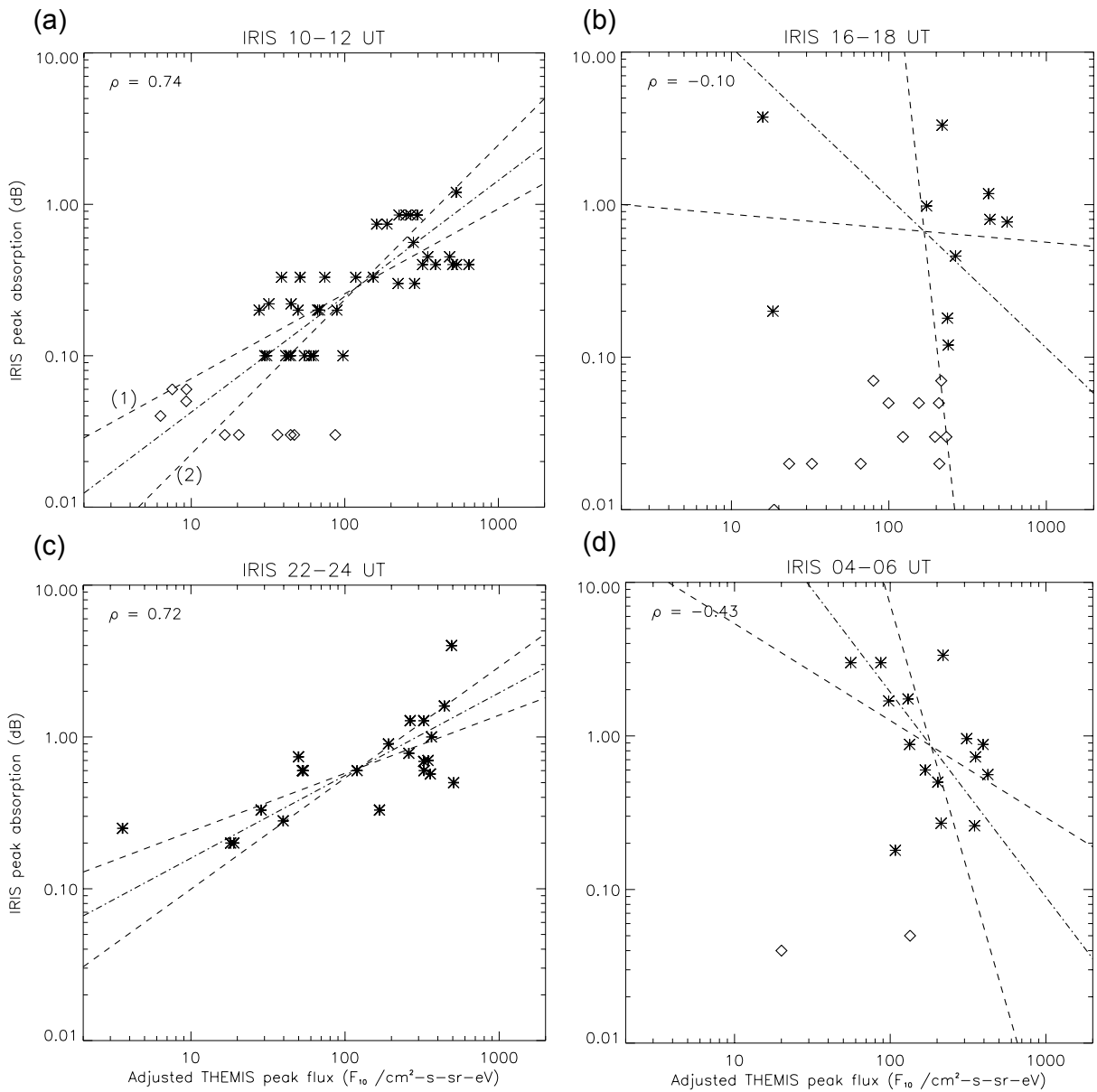


Figure 5: Variation of IRIS peak absorption ( $A$ ) with THEMIS adjusted peak flux ( $F_{10}$ ) for IRIS UT sectors: (a) 10-12; (b) 16-18; (c) 22-24; (d) 04-06. (Regression lines: (1)  $\log(A)$  on  $\log(F_{10})$ ; (2)  $\log(F_{10})$  on  $\log(A)$ .)

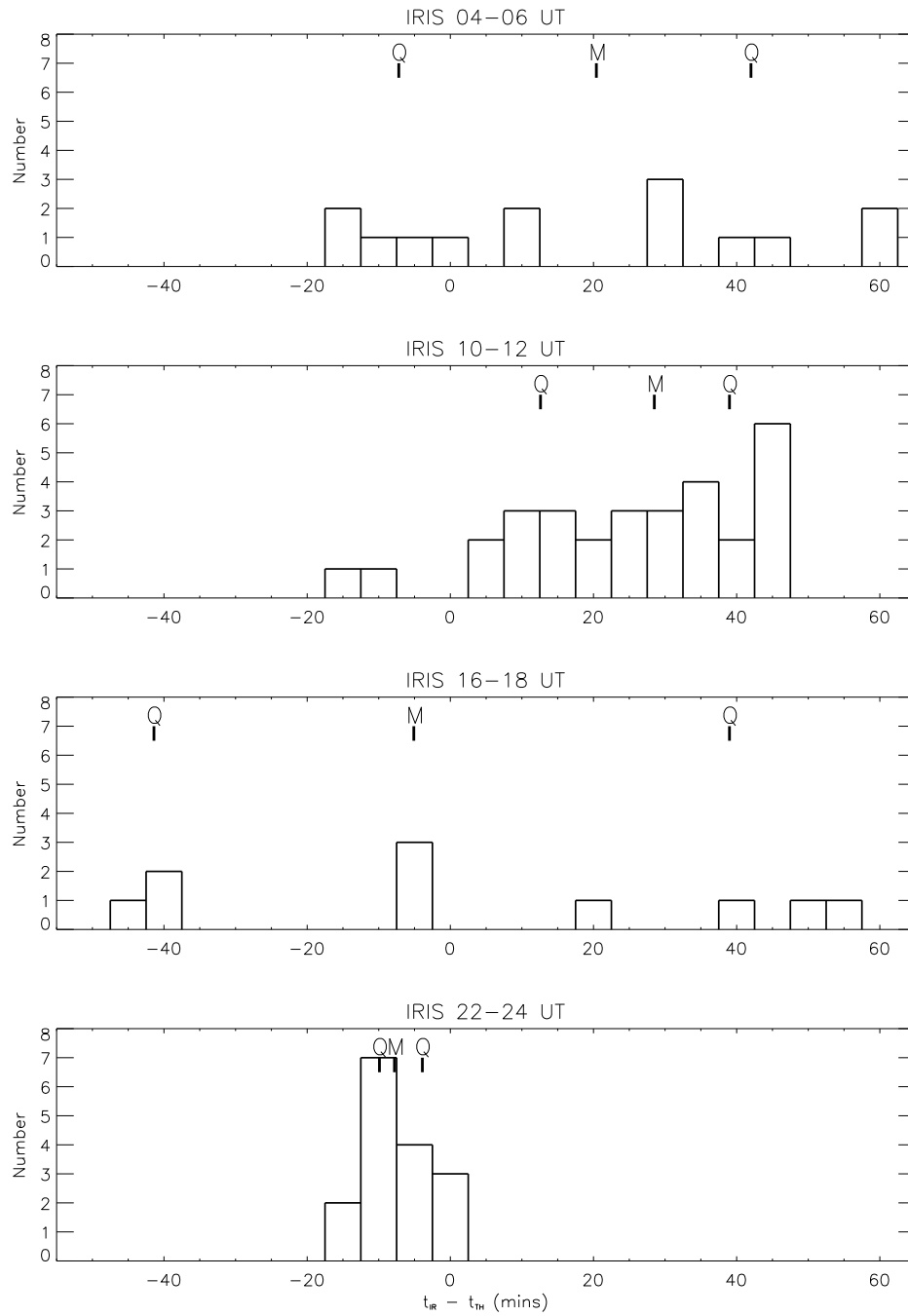


Figure 6: Summary of time differences ( $t_{IR} - t_{TH}$  minutes) for the four IRIS time sectors (M = median; Q = quartiles).

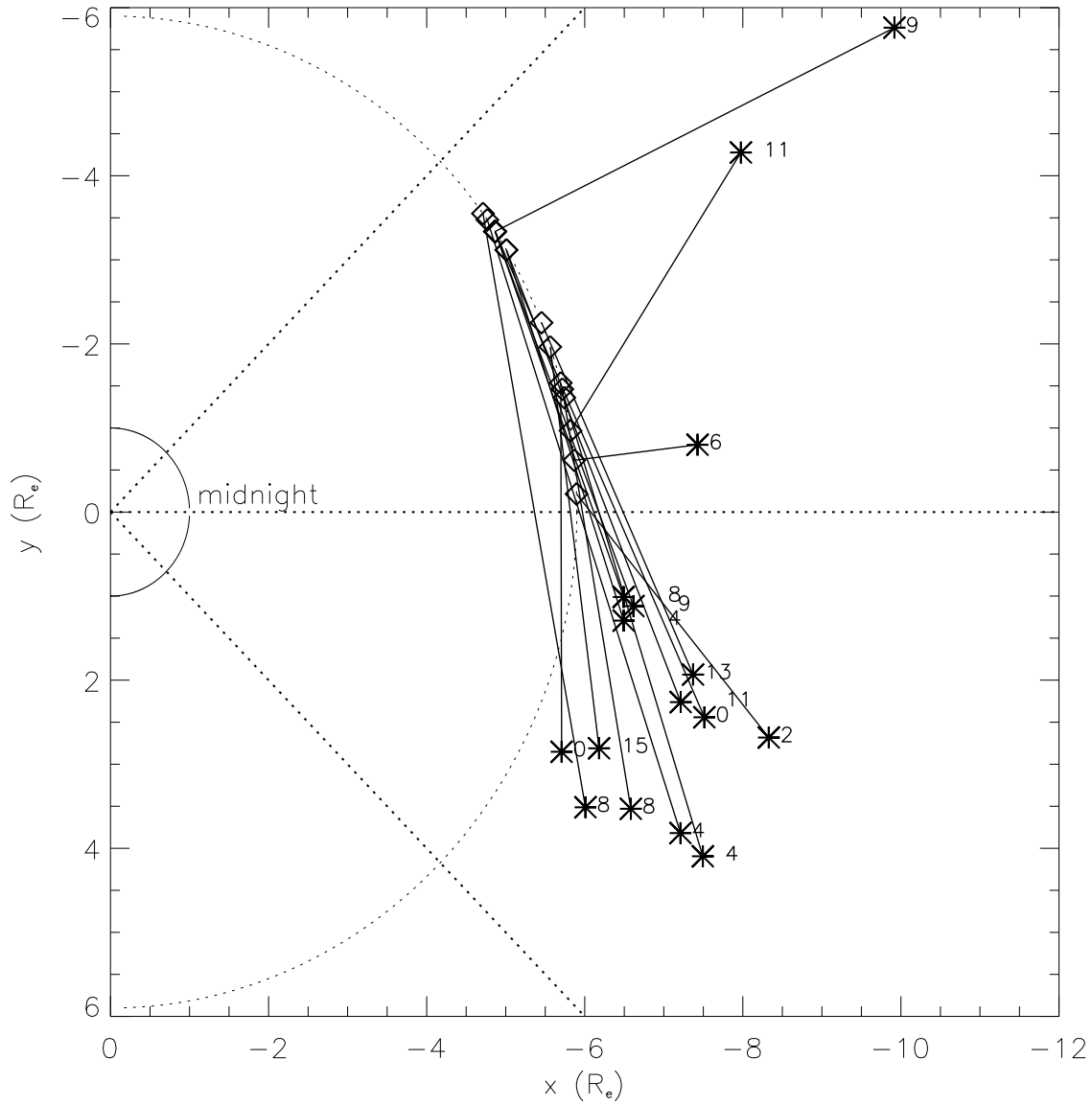


Figure 7: Comparison between nose of field line through Kilpisjärvi (diamonds, at  $L = 5.9$ ) and THEMIS satellite location (asterisks) for individual cases in the midnight sector. The time differences in minutes are marked (the absorption peak precedes the THEMIS flux).



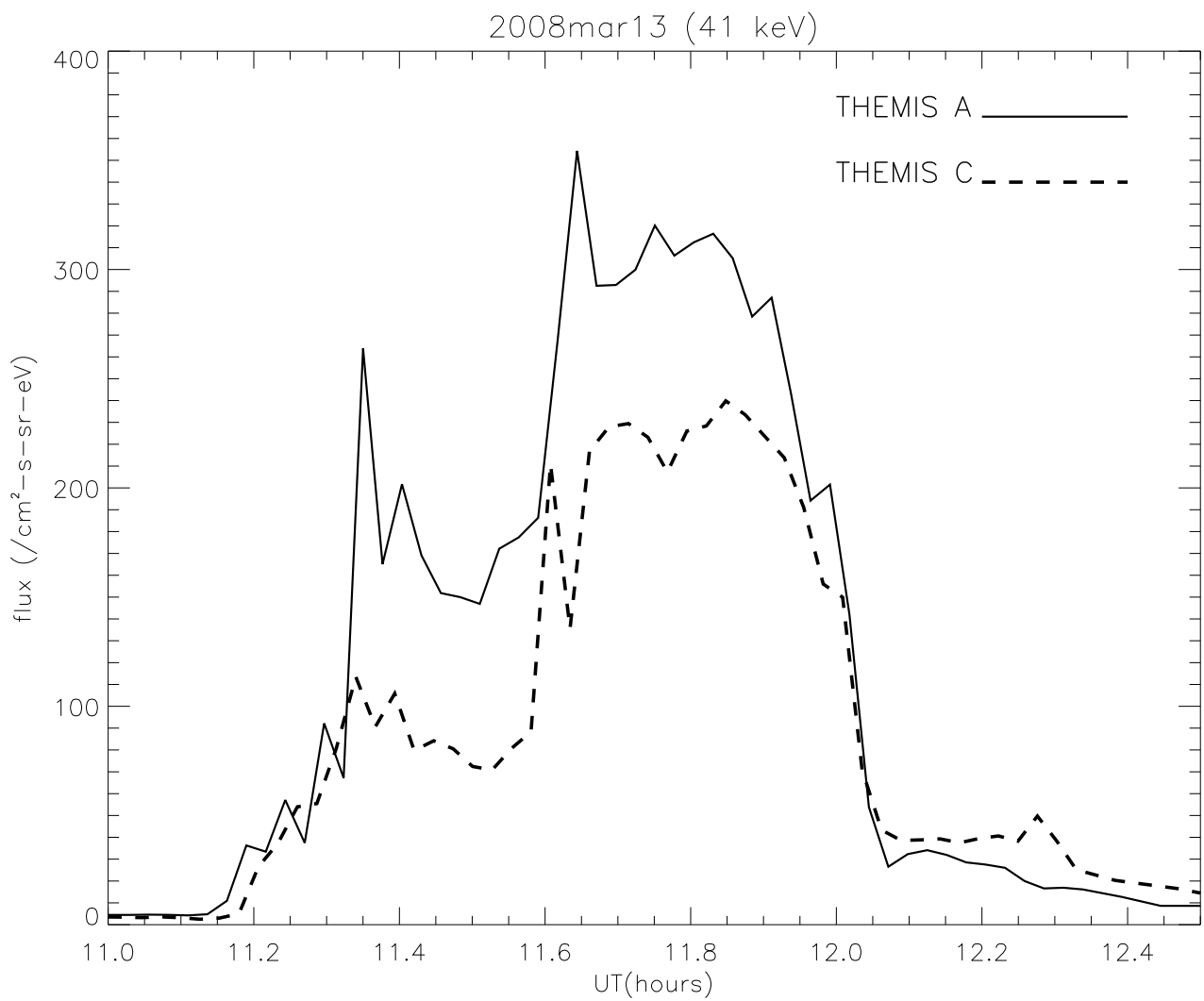


Figure 8: Comparison of 41 keV THEMIS flux profiles between satellites A and C for an event on 2008 March 13, the satellites being  $2.62 R_e$  apart.

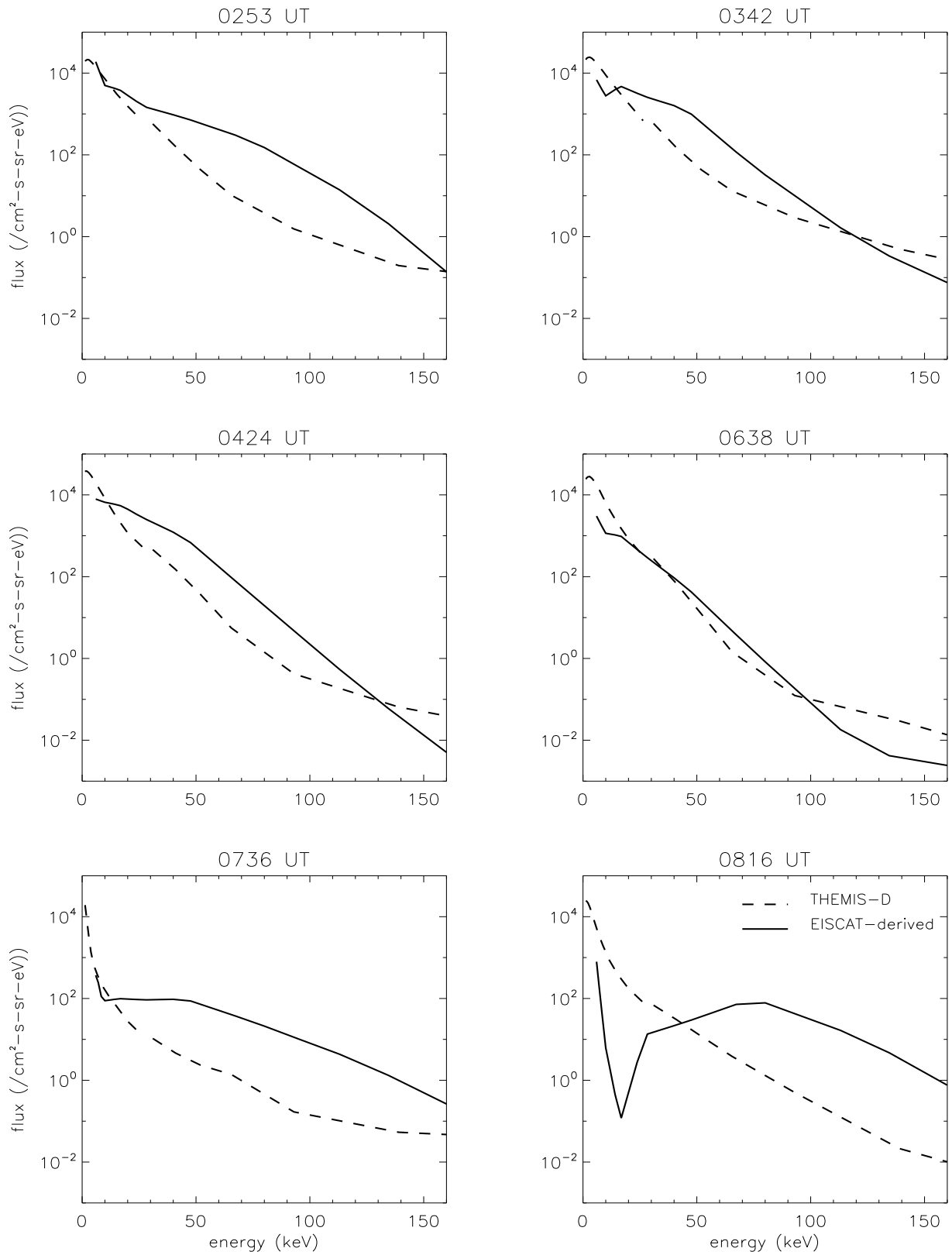


Figure 9: Comparison of THEMIS-D and EISCAT-derived spectra at selected times on the morning of March 9 2008 (solid lines: EISCAT-derived spectra; dashed lines: THEMIS-D spectra).

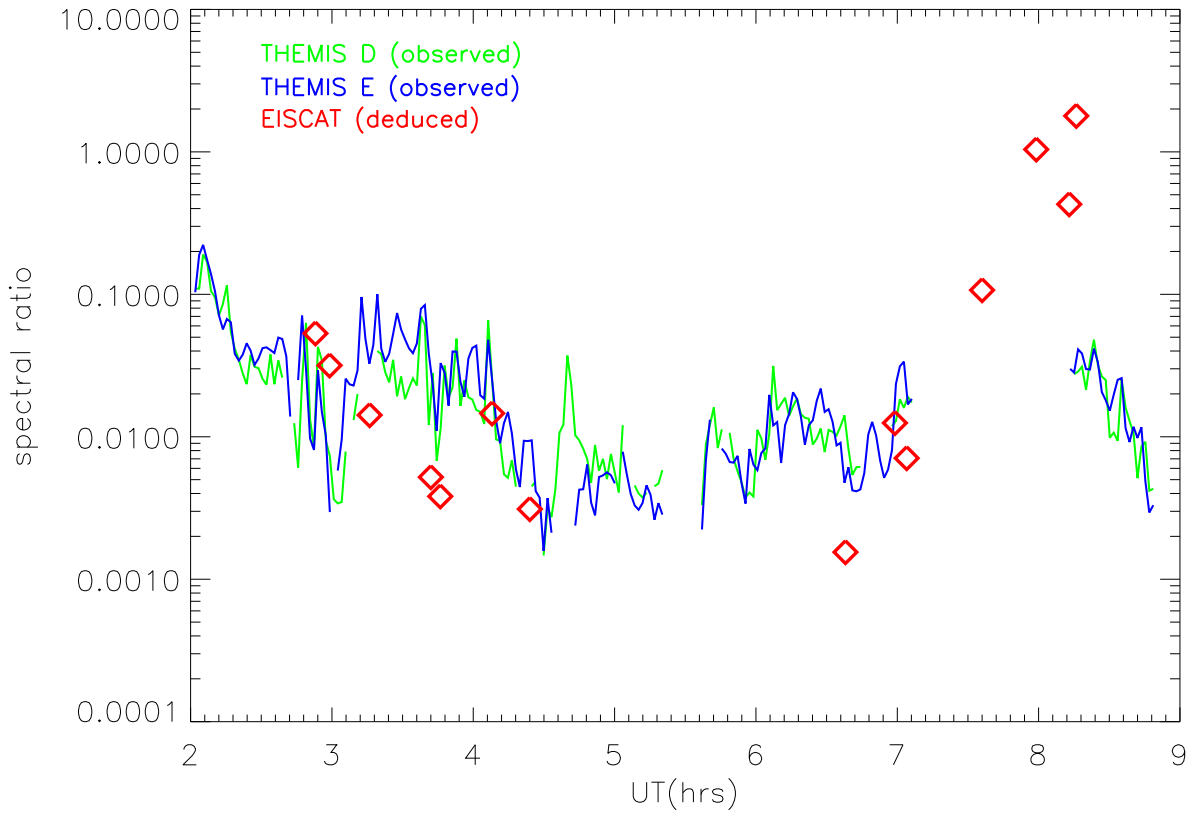


Figure 10: Comparison of spectral hardness: THEMIS D (green); THEMIS E (blue); EISCAT-deduced (red). (Fluxes  $< 0.1 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$  were discarded, which caused the gaps in the THEMIS profiles.)

IRIS UT range	04-06	10-12	16-18	22-24	Total
1. Days considered	52	42	46	54	194
2. Days rejected due to belt contamination	15	4	17	26	62
3. Days without radiation belt contamination (1 - 2)	37	38	29	28	132
4. Days from (3) with measurable 41 keV flux event	22	33	28	21	104
5. Days from (4) with clearly associated abs event $\geq 0.1$ dB	16	18	12	20	66
6. Days from (5) without associated magnetic substorm	0	2	1	0	3

Table 1: General occurrence statistics for the four IRIS sectors. (6. According to SME index (<http://supermag.jhuapl.edu/substorms/>))

Flux range	No. of values	Median (dB)	Range (dB)	Chance (%) of abs being at least	
				1.0 dB	0.3 dB
IRIS 04-06 UT (18 samples)					
$\geq 330$	9	0.50	0.00 - 3.35	11	67
100 - 330	5	0.88	0.18 - 1.69	20	80
33 - 100	0			0	0
10 - 33	4	3.00	0.04 - 3.00	75	75
3.3 - 10	0			0	0
IRIS 10-12 UT (70 samples)					
$\geq 330$	12	0.42	0.26 - 1.19	8	92
100 - 330	16	0.70	0.20 - 1.00	6	69
33 - 100	19	0.10	0.03 - 0.85	0	32
10 - 33	14	0.10	0.02 - 0.50	0	7
3.3 - 10	6	0.05	0.03 - 0.06	0	0
1.0 - 3.3	3	0.05	0.05 - 0.05	0	0
IRIS 16-18 UT (26 samples)					
$\geq 330$	15	0.12	0.00 - 3.32	13	40
100 - 330	6	0.05	0.00 - 0.46	0	17
33 - 100	1	0.03	0.03 - 0.03	0	0
10 - 33	2	3.75	0.01 - 3.75	50	50
3.3 - 10	2	0.20	0.03 - 0.20	0	0
IRIS 22-24 UT (24 samples)					
$\geq 330$	12	0.90	0.50 - 4.00	42	100
100 - 330	3	0.60	0.33 - 0.60	0	100
33 - 100	3	0.28	0.00 - 0.74	0	33
10 - 33	5	0.20	0.10 - 0.60	0	40
3.3 - 10	1	0.25	0.25 - 0.25	0	0

Table 2: Detailed occurrence statistics for the four IRIS sectors (138 samples in total).

Correlated	Partialled-out	22-24 UT (22 values)			10-12 UT (29 values)		
		$\rho_{12,3}$	z	u	$\rho_{12,3}$	z	u
12	3						
logF, logA	r	0.56	0.63	0.4%	0.69	0.84	< 0.1%
logF, r	logA	-0.69	0.85	<0.1%	-0.64	0.75	< 0.1%
logA, r	logF	0.13	0.13	29%	0.20	0.20	16%

Table 3: Results of partial correlation analysis of observed flux (F), strength of absorption (A), and radial distance of satellite (r) for IRIS sectors 22-24 UT and 10-12 UT. ( $\rho_{12,3}$  is the correlation coefficient between parameters 1 and 2 with parameter 3 partialled-out, and u is the probability, based on Fisher's z-transform, that the correlation arose by chance.)

IRIS sector	Noon	Dusk	Midnight	Dawn
UT	10-12	16-18	22-24	04-06
LT (approx)	11.5-13.5	17.5-19.5	23.5-1.5	5.5-7.5
Number of points	38	10	22	15
Correlation coefficient	0.74	-0.10	0.73	-0.43
A on $F_{10}$ regression	$A = 0.019 \times F_{10}^{0.560}$	$A = 1.068 \times F_{10}^{-0.092}$	$A = 0.096 \times F_{10}^{0.390}$	$A = 23.09 \times F_{10}^{-0.632}$
A on $F_{10}$ standard error factor	1.67	3.44	1.65	2.37
$F_{10}$ on A regression	$F_{10} = 413.3 \times A^{0.980}$	$F_{10} = 160.5 \times A^{-0.106}$	$F_{10} = 230.9 \times A^{1.369}$	$F_{10} = 175.6 \times A^{-0.286}$
$F_{10}$ on A standard error factor	1.97	3.78	2.56	1.79
Probability of chance occurrence	$<10^{-4}$	0.21	$10^{-4}$	0.14

Table 4: Regression results between A dB and  $F_{10}$   $\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$  for IRIS in the noon, midnight, dawn and dusk. sectors. (Probability of chance occurrence according to Fisher's z-transform [Fisher, 1921; Moroney, 1951].)

Absorption (A) range	No. of values	Median flux	Range of flux	Chance (%) of flux being in range		
				0 - 10	10 - 100	>100
$0.1 \leq A < 0.3$	6	3	0 - 10	100	0	0
$0.3 \leq A < 1.0$	12	140	0 - 400	8	33	58
$A \geq 1.0$	6	380	200 - 500	0	0	100

Table 5: Detailed occurrence statistics for the midnight IRIS sector, using absorption as the primary selection variable (24 samples in total). These flux values have not been adjusted to  $10R_e$ .