Statistical Properties of Electron Curtain Precipitation Derived with AeroCube-6

M. Shumko[1], A.T. Johnson[1], J.G. Sample[1], D.L. Turner[3], T.P. O'Brien[2], J.B. Blake[2], L.W. Blum[4], A.J. Halford[4]

[1]Department of Physics, Montana State University, Bozeman, Montana, USA
[2]Space Science Applications Laboratory, The Aerospace Corportation, El Segundo, California USA
[3]Johns Hopkins Applied Physics Laboratory, Laurel, Maryland, USA
[4]NASA's Goddard Space Flight Center, Greenbelt, Maryland, USA

Key Points:

- We used the dual AeroCube-6 CubeSats to identify stationary, narrow, and persistent > 30 keV precipitation in low Earth orbit
- A single low Earth-orbiting spacecraft can easily misidentify curtains as microburst precipitation
- A few curtains were persistently scattered into the atmosphere for at least six seconds

Corresponding author: M. Shumko, `msshumko@gmail.com`

Abstract

Curtains are recently discovered stationary, persistent, and narrow in latitude electron precipitation phenomena observed in low Earth orbit over sequential passes of the dual AeroCube-6 CubeSats. The > 30 keV electron curtains were stationary over a variety of spacecraft separations, observed by the follower spacecraft up to 65 seconds after the leader. This study expands the recent curtain discovery and quantifies statistical properties of 1634 curtains observed over three years. We found that in low Earth orbit, many curtains are narrower than 10 kilometers in latitude and 90% are less than 21 kilometers wide. We also found that curtains are an outer radiation belt phenomena that are observed in the late morning and midnight magnetic local time, with a higher occurrence rate at midnight. Furthermore curtains are observed more often at lower geomagnetic activity than microbursts. We compare every statistical result to microbursts to test the hypothesis that curtains are drifting remnants of microbursts. Lastly, we found a few curtains in the bounce loss cone region in the north Atlantic Ocean where drift mission is impossible. In one example, a curtain was continuously scattered for at least six seconds so curtains can be a significant source of > 30 keV electrons into the atmosphere.

1 Plain Language Summary

2 Introduction

Curtains are a stationary electron precipitation phenomena observed in low Earth orbit (LEO). They are narrow in latitude, spiky, and appear stationary for up to a minute between subsequent satellite passes. Blake and O'Brien (2016) recently discovered curtains with the > 30 keV electron dosimeters onboard the dual AeroCube-6 (AC6) CubeSats that operated together between 2014 and 2017. This discovery was possible due to AC6's actively maintained in-track separation between a few hundred meters and a few hundred kilometers. Besides the Blake and O'Brien (2016) discovery study not much is known about curtains including what they are, how are they generated, their statistical properties, and their impact on the atmosphere. Answering these questions is an essential next step towards a more complete understanding of how curtains, and particle precipitation in general, affect the magnetosphere and Earth.

Recently developed multi-spacecraft missions, such as AC6, are necessary to identify and distinguish curtains from similar-looking transient precipitation called electron microbursts. Microbursts have been observed since mid 1960s by high altitude balloons and satellites and are also a spiky increase of electrons shorter than a second but are not spatially stationary (e.g. Anderson & Milton, 1964; Lorentzen et al., 2001; O'Brien et al., 2003; Douma et al., 2017). The companion study to this work by Shumko et al. (2019) calculated the spatial size of microbursts using simultaneous observations of microbursts observe by AC6. The impact of microbursts on the environment is substantial. Thorne et al. (2005), Douma et al. (2019), and Breneman et al. (2017)—among others—estimated that microbursts can deplete the outer radiation belt electrons in about a day. Furthermore, Seppälä et al. (2018) modeled a 6 hour microburst storm and concluded that microbursts depleted mesospheric ozone by roughly 10%. Thus, it is important to understand the connection, if any, between microbursts and curtains. Curtains and microbursts can be easily misidentified from a single spacecraft so we need to reevaluate single-satellite microburst studies. If curtains are numerous then the estimated microburst occurrence rates are overestimated. Furthermore, the microburst impact on the atmosphere and the outer radiation belt is also overestimated.

Blake and O'Brien (2016) proposed the following hypothesis that explains curtain-microburst relationship. If a microburst is not completely lost in the atmosphere after the initial scatter, the remaining microburst electrons will spread out (bounce phase average) along the entire magnetic field line. At the same time these electrons drift to the east, with faster energy electrons drifting at a faster rate, so the initially localized microburst is smeared in longitude into the shape of a curtain. Maybe cite the curtain paper from 2000 that relates them to lightning? Title: Trapped energetic electron curtains produced by thunderstorm driven relativistic runaway electrons.

AC6 does not have the necessary pitch angle, α, resolution to differentiate between drifting and precipitating electrons to test the Blake and O'Brien (2016) hypothesis. Instead we use AC6's position and Earth's asymmetric magnetic field to differentiate particles that are either nearly-trapped or immediately lost in the drift loss cone, and particles immediately lost in the bounce loss cone (BLC). These concepts are described below.

Earth's magnetic field is spatially shifted towards Singapore which creates a region of weaker magnetic field in the South Atlantic Ocean called the South Atlantic Anomaly (SAA). The magnetic field asymmetry caused by the SAA allows barely-trapped particles, defined by a mirror point just above Earth's atmosphere, to mirror much closer to Earth's surface and be lost in the SAA. The barely-trapped particles that are able to execute bounce and drift motion everywhere except the SAA and its conjugate point are in the drift loss cone. The drift loss cone defines a set of α between the trapped and bounce loss cone pitch angles. The particles with pitch angle smaller than the bounce loss cone are unable to complete a full bounce before they are lost in the atmosphere. The convention defining the loss cone is a mirror point at or below 100 kilometer altitude. In this study we will use this definition as well as a more strict convention of a mirror point below sea level.

Without pitch angle resolution, we use AC6's location in LEO to isolate particles that are trapped, barely-trapped, and immediately lost. Above the SAA, AC6 will observe, but not differentiate, particles that are trapped, barely-trapped, and immediately precipitating. In the region outside of the SAA and it's conjugate point, AC6 will observe particles barely trapped in the drift loss cone and immediately precipitating in the bounce loss cone. Lastly, the region in the North Atlantic that is magnetically conjugate to the SAA is the bounce loss cone. Here AC6 only observes particles precipitating within a bounce period (≈ 1.5 second for 30 keV electrons). If a particle makes it to AC6's altitude, it can gyrate past AC6 and precipitate in the North Atlantic. Alternatively, the particle will mirror at or below AC6 and gyrate into the SAA where the equivalent mirror point magnetic field strength is deep in the atmosphere, or below sea level. Thus the particle is lost. Therefore, any precipitation structures observed in the bounce loss cone region must rapidly precipitate.

We estimated the bounce loss cone region in the North Atlantic Ocean using magnetic field modeling. We used the IRBEM-Lib magnetic field library (Boscher et al., 2012) to estimate the local magnetic field strength at a typical 700 km altitude of AC6. Then we traced the magnetic field line that AC6 is on to the southern hemisphere and found the position along the field line with an equivalent field strength as at AC6's location. Since AC6 observed those electrons, the altitude of the equivalent field strength in the SAA represents the upper bound altitude that the bouncing electron will get to. If that position is 100 kilometers or less above Earth's surface we considered that the bounce loss cone. As a more stringent bounce loss cone criteria, we saved the AC6 locations where the conjugate altitude of equivalent field strength is below sea level.

This study expands the Blake and O'Brien (2016) study by estimating statistical properties of curtains and address the Blake and O'Brien (2016) hypothesis. We use 1634 confirmed curtain observations to learn about the distributions of: the curtain width in latitude, the geomagnetic conditions favorable to curtains, and curtain distribution in L and magnetic local time (MLT). Lastly we will address the hypothesis that curtains are drifting remnants of microbursts by showing examples of curtains observed in the bounce loss cone region.

3 Instrumentation

The AC6 mission was a pair of 0.5U (10x10x5 cm) CubeSats built by The Aerospace Corporation designed to measure the electron and proton environment in low Earth orbit (O'Brien et al., 2016). AC6 was launched on 19 June 2014 into a 620x700 km, 98° inclination orbit. The AC6 orbit over the three year mission lifetime was roughly dawn-dusk, and precessed only a few hours in MLT; 8-12 MLT in dawn and 20-24 MLT in dusk. The two AC6 spacecraft, designated as AC6-A and AC6-B, separated after launch and were in proximity for the duration of the three year mission—maintained by an active attitude control system. The attitude control system allowed then to precisely control the amount of atmospheric drag experienced by each AC6 unit using the surface area of their solar panel "wings". By changing their orientation, AC6 was able to maintain a separation between 2-800 km, confirmed with the Global Positioning System. The two AC6 units were in a string of pearls configuration so one unit, typically unit A, was leading the other by an in-track lag—the time it would take the following spacecraft to catch up to the position of the leading spacecraft. To convert between the AC6 in-track separation and in-track lag, we assume a typical 7.5 km/s orbital velocity of LEO spacecraft. The in-track lag was readily available with the Global Positioning System which makes it easy to study precipitation phenomena observed at the same time, and at the same position by shifting one time series by the in-track lag.

Each AC6 unit contains three Aerospace microdosimeters (licensed to Teledyne Microelectronics, Inc) that measure the electron and proton dose in orbit (O'Brien et al., 2016). The dosimeter used for this study is dos1 with a 30 keV electron threshold. dos1 is used for this study because the other dosimeters were not identical between unit A and B. All dosimeters sample at 1 Hz in survey mode, and 10 Hz in burst mode. 10 Hz data was readily available from both AC6 units from June 2014 to May 2017 while their in-track lag was less than 65 seconds, and at times was a fraction of a second. Show a distribution of the in-track lag when they had 10 Hz data? The variety of AC6 separations and data availability over the three-year mission makes it possible to study tranisent electron microburst precipitation (Shumko et al., 2019) and now stationary electron curtain precipitation.

4 Methodology

4.1 Curtain Identification

Outline

1. Various parameters were explored and we tuned it to have as many candidate events as possible while being feasible to inspect every detection.
2. Baseline sensitivity decreases with larger structures, depending on the curtain amplitude, background level, and baseline width. Sensitivity begins to rapidly diminish for widths close to half of the baseline width—around five seconds, correspondent to 38 km size, for this identification criteria.

The 10 Hz data was used to identify curtains with the following two criteria: a high spatial correlation, and bursty. The first criterion quantifies the similarity of the feature between both AC6 units, and the second criterion checks that highly correlated times were bursty. Before we we applied the identification criteria, the AC6-B time series was shifted by the in-track lag to spatially align it with the AC6-A time series.

The first identification criterion is a 1-second rolling Pearson correlation applied to both time series. Spatial features with a correlation greater than 0.8 were considered highly correlated and saved.

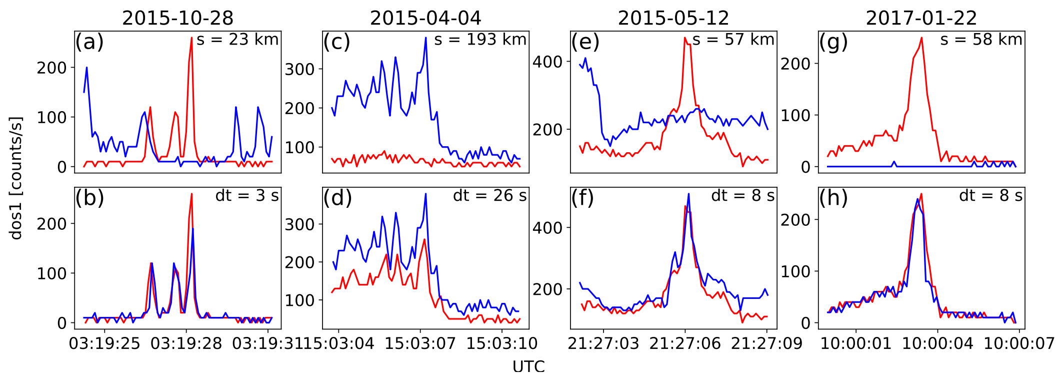

Figure 1. Four examples showing the AC6 > 30 keV electron data taken by AC6 at the same time in the top row and at the same position in the bottom row. AC6-A, whose data is shown with red curves, was s kilometers ahead of AC6-B. To show the data at the same position the time series data from one spacecraft was shifted by the in-track lag and annotated by dt. These examples show curtain precipitation that was highly correlated for up to 26 seconds.

The second identification criterion checks for locations where both AC6 units observed bursty precipitation. Similar to how precipitation bands were identified in Blum et al. (2015) and microbursts in Greeley et al. (2019), we find bursty precipitation by estimating the number of Poisson standard deviations, σ, that a dos1 count rate is above a centered 10-second running average, B_{10}. Locations where the count rates are at least two σ above B_{10} are bursty.

The locations where the two criteria are met are curtain candidates and the time of the peak count rates are saved. To check the quality of the data set, one author visually checked every candidate curtain and 1634 curtains were confirmed. Four curtain examples are shown in Fig. 1. In these examples the unmodified time series is in the top row and the corresponding spatially-aligned time series is in the bottom row. The in-track lag used to shift the bottom row is annotated by dt, corresponding to an AC6 in-track separation annotated by s. The top row is uncorrelated; thus these events were not microbursts. The bottom row is correlated after 3 to 26 seconds. The correlated curtains in the bottom row are peculiar—they have a fine structure on a 10-kilometer scale that we have shown to persist for at least 26 seconds.

5 Results

In the spirit of brevity, we limited the scope of this statistical study to answer three questions:

1. how narrow are curtains,
2. when and where are curtains observed, and
3. are curtains drifting or locally precipitating?

For each of these questions we will compare the curtain distribution against the > 30 keV microburst distribution from Shumko et al. (2019). Then we will provide observational evidence that suggests that some curtain electrons are continuously scattered and can not be drifting.

5.1 Curtain Width

We quantified curtain width in time as the width at half of the curtain's topographic prominence: the height of the peak above the lowest contour that encircles the peak but contains no higher peak. The spatial width of a curtain is the product of the temporal width and the 7.5 km/s orbital velocity mostly in latitude. The distribution of curtain widths is shown in Fig. 2 by the thick black curve. Curtains are very narrow in latitude. Many curtains are less than 10 km wide, and 90% are narrower than 21 km. There is a bias inherent to this detection algorithm. The detection algorithm looses sensitivity to wider curtains so the latitudinal curtain width distribution is likely somewhat underestimated.

We compared the curtain width distribution to the microburst size distribution estimated in Shumko et al. (2019). Shumko et al. (2019) estimated the microburst size distribution by finding microbursts that were observed simultaneously by both AC6 units so the microburst size much be larger than the AC6 separation. The red curve in Fig. 2 shows the microburst distribution estimated from the ratio of the number of concurrent and nonconcurrent microbursts observed in each separation bin.

The curtain and microburst size distributions are very similar with a one notable difference. Curtain widths are observed directly hence their distribution is peaked, while the microburst distribution is estimated from concurrent observations so their distribution is peaked at 0 km AC6 separation. What about the geometric arguments that push the microburst size higher?

5.2 When and Where Are Curtains Observed

The distribution of curtains in L and MLT is shown in Fig. 3. Figure 3a shows the distribution of the 1634 observed curtains and Fig. 3b shows the normalized distribution. The white bins, mostly in the early morning and evening MLT regions, had no observed curtains because the AC6 orbit did not sample there. Figure 3c confirms this by showing the distribution of the number of quality (data quality flag = 0) 10 Hz samples.

After scaling by the uneven sampling in the late morning and midnight MLT regions, the normalized distribution in Fig. 3b shows enhanced curtain occurrence in the outer radiation belt, and in late morning and midnight MLT regions. The highest curtain occurrence rates are near midnight MLT, in contrast to microbursts peak occurrence rates in the late morning MLT (e.g. O'Brien et al., 2003; Douma et al., 2017). Has anyone ever made a L-MLT distribution of low energy microbursts? Most studies that I remember studied 1 MeV microbursts with SAMPEX.

Now we quantify the geomagnetic conditions favorable for curtains. Figure 4 shows the distribution of the Auroral Electroject (AE) index between 2014 and 2017, and the distribution of the AE index when curtains and microbursts were observed. The microburst distribution is from Shumko et al. (2019). Curtains are observed during relatively active times, similar to microbursts, but microbursts typically occur at relatively elevated AE compared to curtains. The microburst peak occurrence rates during quiet times are in the midnight MLT, since curtains are often observed at low geomegtic condtions in the midnight MLT, some of the events at midnight MLT in the prior microburst studies (e.g. Douma et al., 2017) may have been curtains.

5.3 Local Atmospheric Precipitation

6 Discussion

Outline

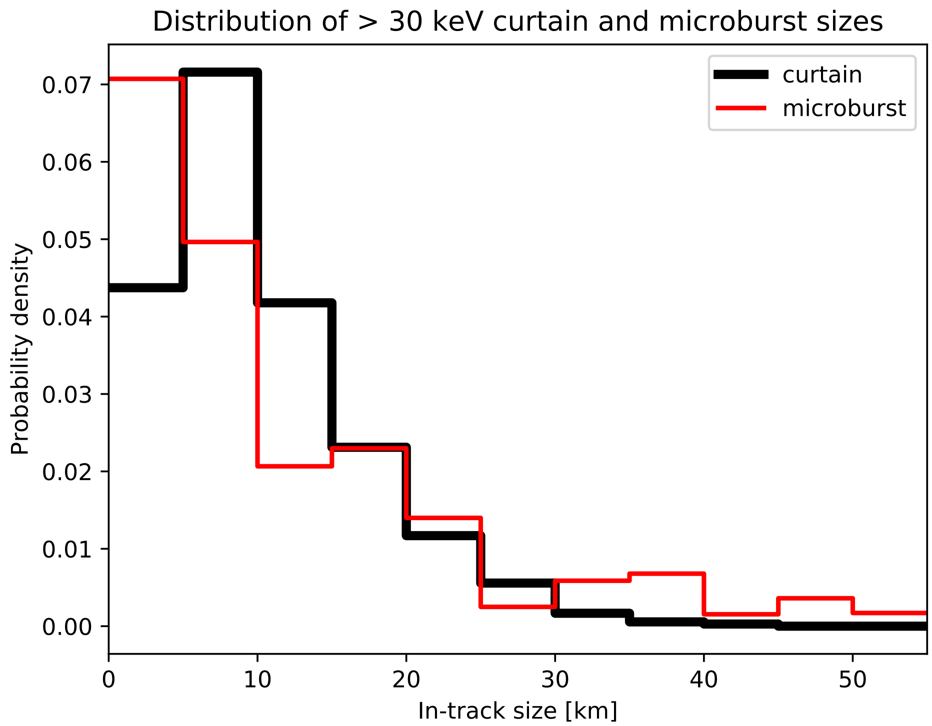

Figure 2. Size distributions of curtains (AC6 in-track separation mostly in latitude) in black and microbursts in red as a function of AC6 in-track width. Microburst distribution adopted from Shumko et al. (2019).

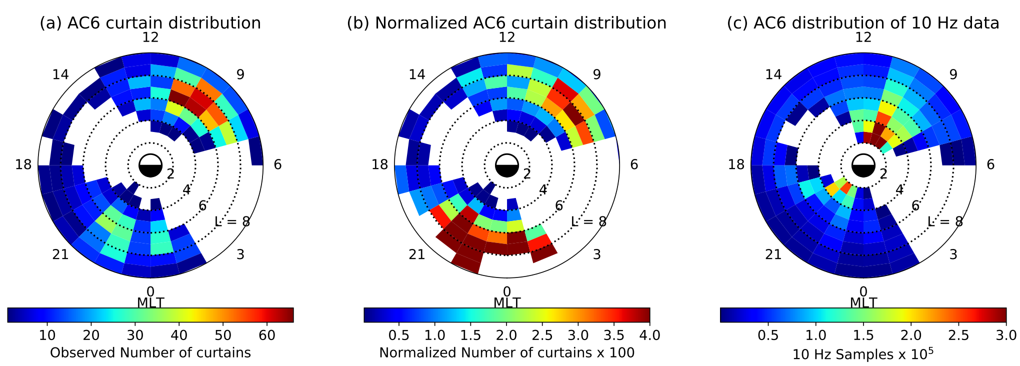

Figure 3. Distribution of observed curtains as a function of L and MLT in panel a and normalized number of curtains in panel b. Panel c shows the number of quality 10 Hz samples taken at the same time that was used to normalize panel b. The white bins in panels a have 0 curtain observations. In panel b the white shaded bins had either 0 detections or very little 10 Hz samples (less than $10,000$).

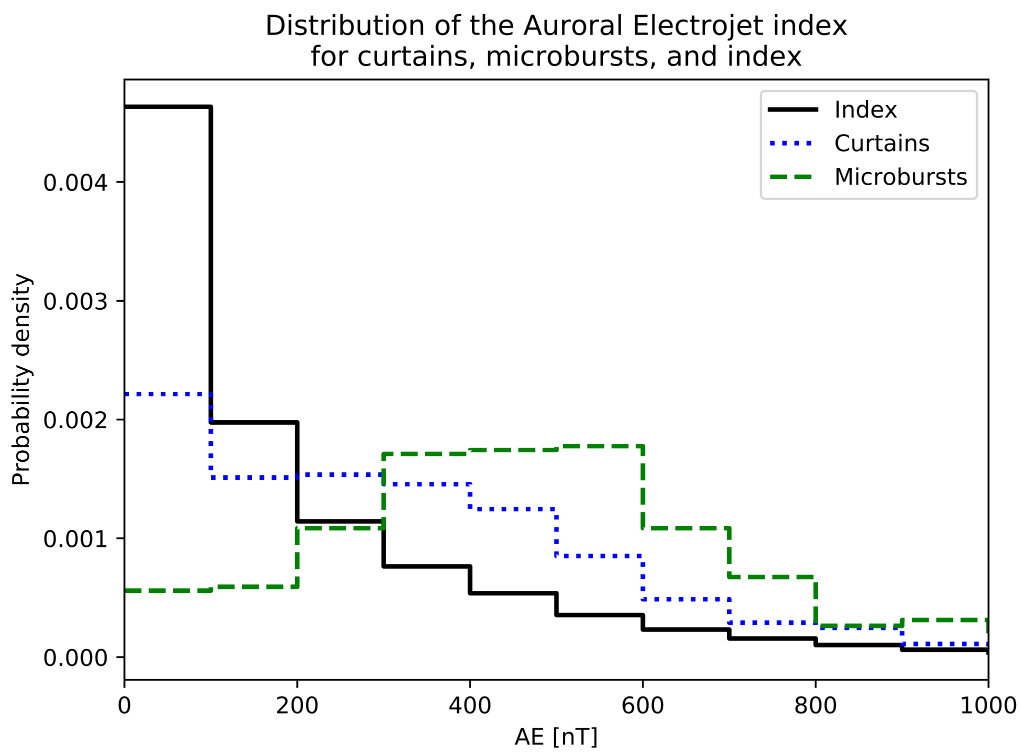

Figure 4. The distribution of the Auroral Electroject (AE) index from 2014 to 2017. The black curve shows the distribution for the entire 2014-2017 AE data set, the dotted blue curve shows the AE distribution for curtains, and the dashed green curve shows AE the distribution for microbursts studied in Shumko et al. (2019).

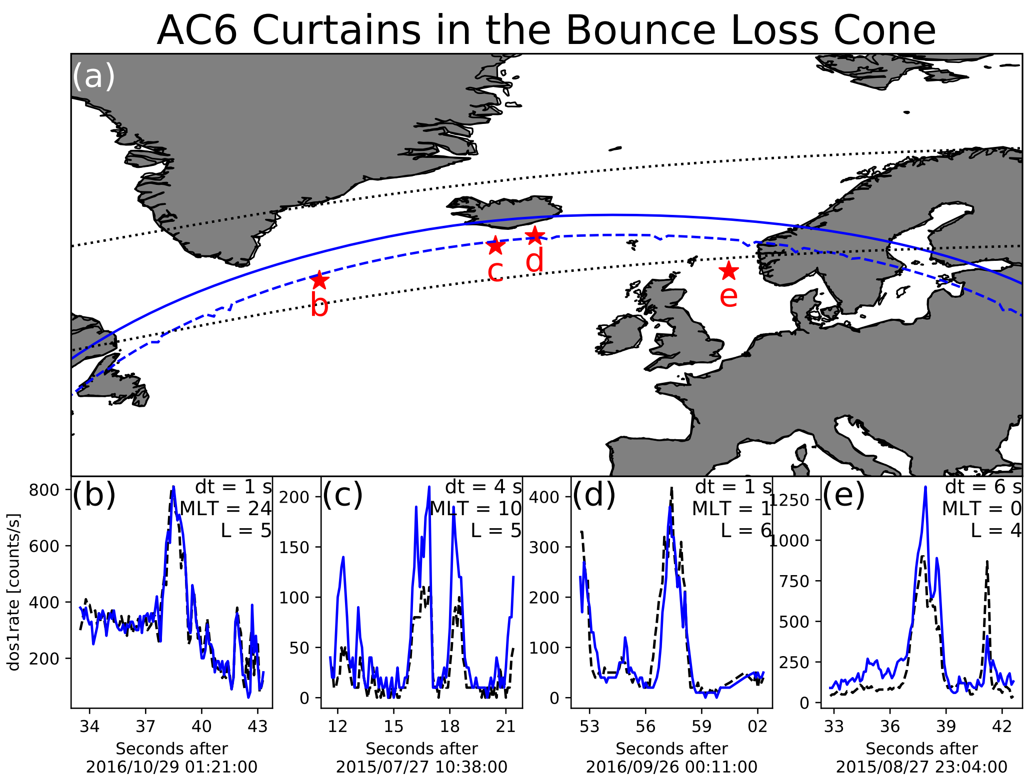

Figure 5. Curtains observed inside the bounce loss cone. Mirror point altitudes assume AC6 is at the 700 km upper bound altitude. Refrence Comess 2013 and DIETRICH 2010 paper that shows a similar BLC region.

1. Curtains are latitudinally narrow and must be around a few hundred km at the equator. Whatever they are they keep their shape for multiple seconds
2. curtain phenomena originates in the outer radiation belt, and observed relatively more in the evening than morning regions. Limited AC6 coverage prevents a complete MLT distribution
3. preference to disturbed conditions
4. To explain the randomness in the leading/following spacecraft count rates. If curtains are microburst remnants and the microburst electrons were recently scattered, then those electrons are not yet mixed homogeneously among the field line. With AC6 the leading and trailing spacecraft will observe a part of the spread out packet. Assuming the microburst had a falling energy spectrum, the leading spacecraft could see a smaller number of higher energy electrons, or a higher number of low energy electrons.
5. some curtains locally precipitate for an extended period of time so there must be a sustained parallel electric field. Show the derivation and estimated potential.
6. AC6 can't answer this question, but curtains could provide a substantial source of HOx and NOX molecules responsible for destroying ozone. We need AC6 with energy and pitch angle resolution.

7 Conclusions

Acknowledgments

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8 Homeless Words

Title: Statistical Properties of Curtains–Latitudinally-Narrow and Persistent Electron Precipitation Phenomena

This study leverages AC6, a multi-spacecraft mission, to interpret and understand particle precipitation in a way that is impossible with a single spacecraft.

This study leverages the asymmetry in Earth's magnetic field. The asymmetric magnetic field results in the SAA and the BLC, two very related and unique regions

Particles that impact the atmosphere are lost during that bounce motion. We found curtains in the bounce loss cone, a region in the North Atlantic near and above Iceland.

The bounce loss cone is magnetically connected to the SAA, where Earth's magnetic field is weakest near Earth's surface. A particle observed in the blc in the northern hemisphere will descend below 100 km altitude. At sub-100 km altitudes the particle has a high chance of encountering and scattering with the atmosphere and be lost.

We found curtain electrons that, when given the chance to execute their cyclical bounce motion, will descend below Earth's surface in the SAA. An electrons can not survive that trip.

Write the paper and ask the question: "What is this paper really about?" Not just curtains, but uncovering something unexpected that has been observed and overlooked for decades.

Are curtains related to aurora? This is a good question—one that is not pertinent here (idea from The Elements of Style p.68).

Here are two parting questions that are not considered here. Why were some curtains shifted slightly? Perhaps it was due to the movement of the magnetic field lines. Also do curtains have a corresponding visual signature on the ground? The answer to this question will show if curtains are related to the aurora.

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