**Abstract**

Curtains are a recently discovered stationary, persistent, and latitudinally narrow electron precipitation phenomenon in low Earth orbit. Observations of curtains over consecutive passes of the dual AeroCube-6 CubeSats with their *>* 30 keV electron dosimeters are found over a variety of spacecraft separations. These events have been observed for up to 65 seconds after the leading spacecraft. This study quantifies the statistical properties of 1,634 curtains observed over three years. We found that in low Earth orbit, many curtains have a latitudinal/radial width less than 10 kilometers in latitude with 90% narrower than 20 kilometers. Curtains are an outer radiation belt phenomena predominantly occurring in the late morning and midnight magnetic local times, with a higher occurrence rate at midnight. Furthermore, curtains are observed more often during geomagnetically active times. We tested the hypothesis that curtains are drifting remnants of microbursts. We found a few curtains in the bounce loss cone region in the north Atlantic Ocean, whose electrons were continuously scattered for at least 6 seconds, as shown in one example. Therefore, curtains may be a significant source of *>* 30 keV electrons into the atmosphere.

# 1 Plain Language Summary

Electron curtain precipitation from space into Earth’s atmosphere is a recently-discovered phenomenon observed by dual-spacecraft missions such as the AeroCube-6 CubeSats that orbit 700 kilometers above Earth’s surface. Curtains appear stationary, remaining unchanged from seconds and up to a minute. Curtains are also very narrow along the satellite orbit (mostly in latitude). Besides these two properties, curtains and their impact on the magnetosphere and atmosphere are not well understood. Some think that curtains are related to another form of electron precipitation called microbursts, and we tested this hypothesis. We found 1,634 curtains observed by the AeroCube-6 mission over three years and quantified their properties to understand their origin better. Curtains and microbursts share many similarities. However, curtains found between Brazil and Africa put this hypothesis in question. A few dozen curtains observed in this North Atlantic region were continuously precipitating into the atmosphere for multiple seconds and are unlikely to be related to microbursts. Therefore, curtains may be a significant source of atmospheric ionization responsible for the natural removal of ozone.

# 2 Introduction

Curtain electron precipitation is a stationary phenomenon observed in low Earth orbit (LEO). Curtains are narrow in latitude and appear stable for up to a minute between subsequent satellite passes. Curtains were recently discovered by Blake and O’Brien (2016) using 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 that varied between a few hundred meters and a few hundred kilometers. Not much is known about curtains including, how they are generated, their statistical properties, and their impact on the atmosphere. Answering these questions is an essential next step towards a complete understanding of how curtains and particle precipitation, in general, affect the magnetosphere and Earth’s atmosphere.

In low Earth orbit, curtains are observed to have a latitudinal width of than a few tens of kilometers in latitude. A polar-orbiting LEO satellite, such as AC6, will pass through their cross-section in about a second. Therefore, in the electron count time series, curtains appear sharply peaked. AC6 also observes similar-looking transient precipitation called electron microbursts. Both microbursts and curtains are peaked in the AC6 data for different reasons: microbursts primarily for being temporally short, and curtains primarily for being narrow in latitude. Hence AC6, and other recently developed multi-spacecraft missions, are necessary to identify and distinguish between curtains and microbursts.

Since the mid-1960s, microbursts have been observed by high altitude balloons where they also appear as sharp peaks with a sub-second duration (e.g., Anderson & Milton, 1964; Brown et al., 1965; Parks, 1967). Because balloons are relatively stationary, a microburst is easily classified as a transient phenomenon. Microburst electrons have also been directly observed by LEO satellites such as The Solar Anomalous and Magnetospheric Particle Explorer (e.g., Lorentzen, Blake, et al., 2001; O’Brien et al., 2003; Douma et al., 2017). But precipitation that looks like a microburst from a single LEO satellite is ambiguous—it can be transient, stationary and narrow in latitude, or both. Thus, multi-spacecraft missions such as the Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (Johnson et al., 2020, FIREBIRD-II) and AC6 (O’Brien et al., 2016) are necessary to resolve this ambiguity. While this study focuses on stationary precipitation, microbursts that were observed simultaneously by AC6 have been studied in Shumko et al. (2019).

The impact of microbursts on the outer Van Allen radiation belt and Earth’s atmosphere can be substantial. Lorentzen, Looper, and Blake (2001), Thorne et al. (2005), Breneman et al. (2017), and Douma et al. (2019)—among others, estimated that microbursts could deplete the outer radiation belt electrons in about a day. Furthermore, Sepp¨al¨a et al. (2018) modeled a 6-hour microburst storm and concluded that microbursts depleted mesospheric ozone by roughly 10%. However, the impact of curtains is unknown, so it is crucial to understand the connection, if any, between microbursts and curtains. Curtains and microbursts can be easily misidentified from a single spacecraft, so we may need to reevaluate single-satellite microburst studies. If curtains are numerous, then the atmospheric impact associated with microburst observations from single satellites may be overestimated.

Blake and O’Brien (2016) proposed a hypothesis that curtains are drifting remnants of microbursts. If a microburst is not entirely lost in the atmosphere after the initial scatter, the remaining microburst electrons will spread out (bounce phase disperse) along the entire magnetic field line over a few bounce periods. Concurrently these electrons drift to the east, with higher energy electrons drifting at a faster rate. Therefore, if this hypothesis is correct, the initially localized microburst is spread out in longitude into the shape of a curtain. The idea of curtains is not entirely new, and Lehtinen et al. (2000) predicted that energetic runaway beams driven by lightning could also create curtains.

This study expands on Blake and O’Brien (2016) by estimating the statistical properties of curtains. We use 1634 confirmed curtain observations to study the distributions of curtains with respect to latitudinal width, geomagnetic activity, and their distribution in L and magnetic local time (MLT). Lastly, we will address the hypothesis that curtains are drifting remnants of microbursts and show examples of curtains observed in the BLC region.

# 3 Instrumentation

The AC6 mission was a pair of 0.5U (10x10x5 cm) CubeSats built by The Aerospace Corporation and 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, 98inclination 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 the dawn and 20-24 MLT in the dusk sector. 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 them 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 va separation between 2-800 km, confirmed by 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, the AC6 orbital velocity was used. AC6’s orbital velocity was 7*.*6 km/s and varied by as much as 0*.*1 km/s. 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 the same position by shifting one-time series by the in-track lag.

Each AC6 unit contains three Aerospace micro dosimeters (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. Only dos1 is used for this study as the other dosimeters either responded primarily to protons or were not comparable 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. Figure A1 shows the distribution of 10 Hz data as a function of AC6 in-track lag. The variety of AC6 separations and data availability over the three-year mission makes it possible to study transient electron microburst precipitation (Shumko et al., 2019) and now stationary electron curtain precipitation.

# 4 Methodology

**4.1 Curtain Identification**

The 10 Hz data was used to identify curtains with two criteria that are described below: a high spatial correlation, and prominently peaked. Before we applied the identification criteria, the AC6-B time series was shifted by the in-track lag to align it with the AC6-A time series spatially.

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 are considered highly correlated. The second criterion is applied to any highly correlated features to check if they are also prominently peaked. To find peaked precipitation, we used a method similar to the technique used by Blum et al. (2015) to identify precipitation bands, and by Greeley et al. (2019) to identify microbursts. Our method quantified the number of Poisson standard deviations, *σ*, that a dos1 count rate is above a 10-second centered running average,√ *B*10. Locations where dos1 is at least two *σ* above *B*10, in other words, *dos*1 *>* 2 *B*10 + *B*10, are considered prominently peaked.

We tuned the detection parameters to identify many candidate curtains while being feasible to check every detection. One author visually inspected 6,149 candidate curtains, and 1,634 quality curtains were confirmed. Four curtain examples are shown in Fig. 1. In each instance, the unmodified time series is shown in the top row and the spatially aligned time series 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 bottom row shows highly correlated curtains observed at the same location for at least 3 to 26 seconds.

**4.2 Differentiating Between Drifting and Precipitating Curtains**

The AC6 dosimeters lack the necessary pitch angle resolution to differentiate between drifting and precipitating electrons to test the Blake and O’Brien (2016) hypothesis that curtains are the drifting remnants of microbursts. Fortunately, one standard method of distinguishing between precipitating, drifting, and trapped particles are using particle measurements in conjunction with the location of the South Atlantic Anomaly (SAA).

Earth’s magnetic field is asymmetric and has a region of a weaker magnetic field in the South Atlantic Ocean called the South Atlantic Anomaly. The weaker magnetic field in the SAA naturally differentiates particles by pitch angle into trapped and quasi-trapped populations. While some particles observed in LEO are trapped and will execute closed drift paths, most particles found in LEO are quasi-trapped: they drift around the Earth until they reach the SAA. Within the SAA, the weaker magnetic field strength can lower the particle’s mirror point altitude into the atmosphere, where collisions with the atmospheric neutrals and ions are more numerous, and the particle is lost.

Particles that are quasi-trapped have pitch angles in the drift loss cone and will precipitate within one drift period (often within the SAA). Particles with smaller equatorial pitch angles (less than ≈ 6◦) that are lost in the atmosphere within one bounce are in the bounce loss cone (BLC). Traditionally, we define a BLC particle if its mirror point altitude is at or below 100 km in either hemisphere.

For most energies of particles in most regions outside of the SAA and their conjugate points in the North Atlantic, AC6 will observe a combination of drift and bounce loss cone particles. In the SAA, AC does not only observe electrons that are immediately lost but a combination of electrons that are in the drift loss cone, bounce loss cone, and trapped. A trapped electron that locally mirrors at AC6’s altitude in the SAA will reflect at higher altitudes everywhere else. In the region magnetically conjugate to the SAA in the North Atlantic, AC6 only observes electrons in the BLC. Here, if an electron makes it to AC6’s altitude, it might be in the local loss cone and is statistically likely to precipitate in the local hemisphere. Alternatively, the electron can mirror at or below AC6 and bounce to its conjugate mirror point deep in the atmosphere or below sea level in the SAA. Therefore, any electrons observed in the BLC region must rapidly precipitate.

We estimated the BLC region for locally-mirroring electrons in the North Atlantic Ocean using the IRBEM-Lib magnetic field library and the Olson-Pfitzer magnetic field model (Boscher et al., 2012; Olson & Pfitzer, 1982). We defined a latitude-longitude grid, with a ≈ 0*.*5◦ × 0*.*5◦ grid size, spanning the North Atlantic at 700-kilometer altitude (a typical altitude for AC6), and estimated the local magnetic field strength. For each latitude-longitude point, we traced the magnetic field line to the southern hemisphere and found the conjugate mirror point altitude. If the conjugate mirror point is >= 100 kilometers, the electron is likely lost, and the associated grid point is considered to be in the BLC. Furthermore, a more rigorous bounce loss cone criterion is the conjugate mirror point altitude below sea level. In this case, the electron is highly likely to be lost. Since AC6 can measure locally mirroring electrons in the North Atlantic, the spacecraft altitude determines the upper bound conjugate mirror point altitude in the SAA. The BLC region estimated by this method closely matches the BLC region shown in Comess et al. (2013, Figure 1) and Dietrich et al. (2010, Figure 3). Furthermore, we repeated the same analysis using the Tsyganenko 1989 model (Tsyganenko, 1989), which yielded similar boundaries.

# 5 Results

In this study, we answered three questions:

1. What is the distribution of curtain widths in latitude?

2. When and where are curtains observed?

3. Are curtains drifting or locally precipitating?

We then compared some of these results to the *>* 30 keV microburst distribution from Shumko et al. (2019).

**5.1 Curtain Width**

We quantified the curtain width in the dos1 time series 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 then the product of the observed width in time and AC6’s orbital velocity. The curtain width is measured along AC6’s orbit track, which is mostly in latitude. Therefore the estimated curtain widths are also mostly in latitude. The distribution of curtain widths is shown in Fig. 2 by the thick black curve. The curtains are very narrow. Many curtains are thinner than 10 km in latitude, and 90% are narrower than 20 km in latitude.

We then 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 with microbursts that were observed simultaneously by both AC6 units. Thus, the microburst size must be larger than the AC6 separation. The red curve in Fig. 2 shows the microburst distribution estimated as the ratio of the number of simultaneous microbursts to all microbursts observed in each separation bin.

**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 observed curtains, while Fig. 3b shows the same distribution normalized by the number of quality 10 Hz samples that AC6 took at the same location in each L-MLT bin. This normalization is shown in Fig. 3c. The normalized curtain distribution in Fig. 3b shows an enhanced curtain occurrence in the outer radiation belt in the late morning and midnight MLT regions.

We also quantified the geomagnetic conditions favorable for curtains. Figure 4a shows the distribution of the minute cadence Auroral Electroject (AE) index between 2014 and 2017 in solid black. Furthermore, the distribution of the AE index when curtains were observed is shown by the solid blue lines, and when microbursts were found by the



dashed green lines. Both microbursts and curtains are observed during active geomagnetic times, but curtains are also found relatively more often at low geomagnetic activity. Lastly, we normalized the microburst and curtain distributions in Fig. 4a assuming an unrealistic, but insightful, scenario where any AE index is equally probable. The normalized distributions are shown in Fig. 4b and they emphasize that both curtains and microbursts occurrence frequency increases with the AE index.

**5.3 Local Atmospheric Precipitation**

Figure 5a shows a map of the northern BLC region in the North Atlantic. The solid blue line is the northern boundary where an electron that mirrors locally at 700 km has a conjugate mirror point at 100 km in the SAA. Immediately south of the solid blue line, the conjugate mirror altitude rapidly decreases towards sea level. The dashed blue line is the boundary where the conjugate mirror point altitude is at sea level. South of this line, the mirror point is inside the Earth. For reference, AC6 takes about 30 seconds to move between the solid and dashed blue curves. The two dotted black curves in Fig. 5a is roughly the boundary of the outer radiation belt, defined as L = 4 − 8.

We found 36 curtains that were observed inside the BLC region. Figure 5b-e shows four curtain examples (AC6-B time-shifted by the in-track lag), along with the AC6 in-track lag, L and MLT during the observations annotated. The AC6 locations where these curtains were observed are shown in Fig. 5a with the red stars and the corresponding panel labels.

# 6 Discussion

**6.1 Curtain Width**

Curtains are very narrow in latitude. Figure 2 shows that the width of most curtains is on the order of 10 kilometers, and 90% are narrower than 20 km. Scaled to the magnetic equator, where we presume curtains are generated, these widths correspond to a source with a radial scale size of a few hundred kilometers. As shown in Fig. 1, it is remarkable that some curtains remain stationary and maintain a fine structure after multiple seconds with little observable difference. However, some curtains appear to be slightly and systematically shifted in latitude while maintaining their fine structure (not shown).

If curtains are remnants of microbursts, then the distribution of curtain widths in latitude should correspond to the microburst size distribution. Figure 2 shows a good correspondence between the distribution of curtain widths in latitude and the microburst size distribution from Shumko et al. (2019). Therefore, it is reasonable to believe that curtains and microbursts are related, but this result needs to be carefully inspected for sources of bias.

The microburst scale size distribution, as described in Shumko et al. (2019), is the fraction of microbursts observed simultaneously to all microbursts observed either simultaneously or by only one AC6 unit. A microburst observed simultaneously must be larger than the spacecraft separation, so the microburst distribution is a lower bound. Furthermore, the detection algorithm described in section 4.1 loses sensitivity for wider curtains. For curtains with a width similar to the detection algorithms 10-second baseline, the baseline will be elevated, making the curtain peak less pronounced. The result of this bias is similar to the bias inherent in the microburst distribution—both distributions are underestimated. These biases are difficult to quantify, but we believe that they are likely too small to qualitatively change the interpretation that microburst and curtain size distributions are similar.

**6.2 When and Where Are Curtains Observed**

Figure 3b shows that curtains likely originate in the outer radiation belt and are observed relatively more in the late evening than late morning regions. Unfortunately, the limited AC6 coverage prevents a complete curtain distribution in MLT. This distribution, though limited, appears to be similar to the L-MLT distribution of microbursts from prior studies (e.g., O’Brien et al., 2003; Douma et al., 2017). The MLT region with the most frequently observed curtains and microbursts are opposite: microbursts are preferentially found in the late morning, while curtains are mainly seen near midnight. The statistics at high L are somewhat limited because AC6 rapidly crosses high L shells. Nevertheless, Fig. 3b hints that curtains near midnight MLT were observed to L shells possibly outside the outer radiation belt.

Figure 4 shows that the microburst and curtain observations are both associated with an enhanced AE, although curtains show a slight preference to lower the AE index. Assuming the Blake and O’Brien (2016) hypothesis, one possible explanation is that during quiet conditions, the remnant microburst electrons are more likely to drift undisturbed, and AC6 is more likely to observe the fine, highly-correlated curtain structure. In contrast, during active conditions, the curtain electrons are still drifting. Still, the dynamics of an actively-changing magnetosphere can easily perturb curtain electrons until AC6 no longer observes a highly correlated structure at the same location.

**6.3 Curtains Observed in The Bounce Loss Cone**

~~The evidence presented so far hint at, but not directly confirm, that curtains are~~

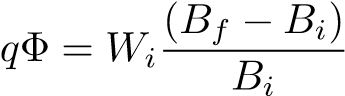
~~connected to microbursts. But the few curtains that were observed in the bounce loss~~

~~cone and shown in Fig. 5 put the hypothesis into question.~~ The observations of curtains in the bounce loss cone can perhaps provide clues to what the generation mechanism may be. These curtains were observed near the sea level mirror altitude curve. Thus they were not drifting and were precipitating for as long as 6 seconds, as shown in Fig. 5e. The curtain precipitation persisted for multiple bounce periods (≈ 1*.*5 seconds for 30 keV electrons in this region). This is a surprising result because there are relatively few mechanisms capable of persistently scattering electrons. This mechanism must be radially localized near the magnetic equator, on a scale of a few hundred kilometers. A candidate mechanism is a direct current electric field that is parallel to the background magnetic field that lowers the electron mirror point to AC6 altitudes.

To find the minimum potential, we assume the electron is barely trapped and has a 100-kilometer conjugate mirror point altitude in the SAA, so initially, the electron will mirror above AC6 in the bounce loss cone region. To find the parallel potential, *q*Φ, we use the kinetic energy, *W*, of a 30 keV electron at its initial mirror point with a magnetic field strength of *Bi*. The kinetic energy at the initial mirror point can be written as *Wi* = *µBi,* where *µ* is the first adiabatic invariant that is conserved during this acceleration. When a parallel potential acts on the electron of charge *q* and does *q*Φ amount of work, the electron will mirror closer to Earth’s surface and mirror at a field strength *Bf* where its final energy is *Wf* = *µBf*. Now we relate the initial and final kinetic energy of the electron,

*µBf* = *µBi* + *q*Φ*.* (1)

Then we solve for *q*Φ and substitute *µ* to express the above equation as a function of the initial kinetic energy

*.* (2)

The parallel potential is proportional to *Wi,* so a larger potential is necessary to accelerate higher energy electrons. AC6 dos1 electron energy response increases rapidly from 30 keV to a peak at 100 keV (O’Brien et al., 2019, Figure 2), therefore our assumption that *Wi* = 30 keV will underestimate the parallel potential. In reality, the counts observed by AC6 is a convolution of, among other things, the AC6 dos1 electron energy response and the falling electron energy spectrum. Thus, the majority of electrons that AC6 observed have energies close to 30 keV, and the *Wi* = 30 is an appropriate approximation.

We again used IRBEM-Lib to estimate *q*Φ. For each example, the curtain in Fig. 5, we first estimated the local magnetic field, *Bf*, that the electron descended to after the acceleration. Then we traced the local field line into the SAA. We estimated *Bi* at 100 kilometers altitude in the SAA for barely trapped electrons. With the initial and final *B*, along with *W* = 30 keV, the minimum potential was between *q*Φ = 1 − 4 kV for the four examples shown in Fig. 5.

The range of estimated potentials is typical for the aurora. Partamies et al. (2008) used the observations made by the Fast Auroral SnapshoT (FAST) mission. They reported that the auroral inverted-V electron precipitation structures, with electron energies up to a few tens of keV, were accelerated by 2-4 kV parallel potentials. The inverted-V structure and curtains share several similarities, including their energy, latitudinal width, and high occurrence rate in the midnight MLT region. A possible connection between the inverted-V structures is intriguing, but by itself, AC6 cannot easily test this hypothesis. A follow-on study can incorporate the list of observed curtains with ground-based auroral imagers and look for simultaneous occurrence of curtains and mesoscale auroral arcs.

Outside of the BLC, the lack of pitch angle and energy information makes the AC6 electron data ambiguous. Still, the curtains observed in the BLC suggest that some curtains continuously precipitate for multiple seconds. Curtains could be a significant source of energetic electrons into the atmosphere. Energetic electron precipitation produces odd Nitrogen (HOX) that is currently underestimated by atmospheric models such as the widely used Whole Atmosphere Community Climate Model (WACCM) (e.g., Randall et al., 2015). A comprehensive study of the curtain impact on the atmosphere can be done with an AC6-like mission with pitch angle and energy resolution.

# 7 Conclusions

The 1,634 confirmed curtains allowed us to make the following inferences:

1. Curtains are very narrow, —90% are less than 20 kilometers wide in latitude.

2. Curtains are observed in the outer radiation belt, predominately in the midnight and the late morning MLT regions, and during active geomagnetic periods.

3. Some curtains continuously precipitate into the atmosphere for multiple seconds.

Curtain precipitation is remarkably narrow, with a fine structure that persists for multiple seconds. Either the scattering mechanism that continuously generates curtains is physically static for multiple seconds, or the curtain electron drift is often undisturbed.

The curtain-microburst relationship hypothesized in Blake and O’Brien (2016) is

not clear. The two results in support of the hypothesis are: curtain width and microburst

size distributions are very similar, and the limited AC6 coverage in MLT shows that both

occur in similar locations in the magnetosphere. But curtains observed in the bounce

loss cone complicate this interpretation. Some curtains continuously precipitate for at

least a few seconds and can be a significant source of energetic electron precipitation

into the atmosphere. Lastly, we found that the continuous scattering of curtain electrons

can be explained by a parallel direct current electric field, possibly relating curtains to the aurora.