

Duration of Individual Relativistic Electron Microbursts: A Probe Into Their Scattering Mechanism ... **Better/shorter title?**

M. Shumko¹, L.W. Blum², and A.B. Crew³

¹NASA's Goddard Space Flight Center, Greenbelt, Maryland

²University of Colorado Boulder, Boulder, Colorado

³Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland

Key Points:

- We identified relativistic microbursts observed by the SAMPEX satellite and quantified their duration
- The microburst duration is shortest at midnight and longest at noon magnetic local times.
- Whistler-mode chorus rising tone element duration has a similar trend

Abstract

In this study we used the Solar Anomalous and Magnetospheric Particle Explorer to identify relativistic, > 1 MeV, electron microbursts and we quantified their duration. We found the shortest microbursts, with a median duration around 80 milliseconds, near midnight magnetic local time. Microburst duration increases through dawn and to noon magnetic local time, where the median microburst duration roughly doubles to 160 milliseconds. The increasing microburst duration trend in magnetic local time is similar to the whistler mode chorus rising tone element duration, shedding light into the microburst scattering mechanism.

Plain Language Summary

Microbursts are a naturally occurring form of electron precipitation from the near-Earth space into the atmosphere. They are characterized by their short duration, typically defined to be less than a second, or sometimes as 100 milliseconds... Microburst impact on the atmosphere includes the degradation of Mesospheric Ozone through the production of Odd Nitrogen and Odd Hydrogen molecules... We don't know the details on how microburst electrons are scattered, but there is evidence that they are scattered by whistler-mode chorus rising tone elements... Talk about duration and how it is a probe into the scattering physics.

1 Introduction

Outline

1. Introduce particle accelerating/scattering mechanism... dual role of chorus waves.
2. One manifestation of electron-chorus scattering are electron microbursts.
3. Briefly describe microbursts and their properties.
4. Mention the chorus-microburst link, but it is currently unknown the physics of how electrons get scattered. Two approaches are quasi-linear diffusion and non-linear scattering.
5. Talk about microburst-chorus rising tone element duration and how they are similar. Mention the prior microburst width studies.
6. The microburst width has not been explored as a function of geomagnetic indices or location.
7. The trends in microburst width (duration) can be a probe into the conditions necessary to scatter microburst electrons.

Earth's outer radiation belt particle population is in constant flux, governed by many processes that affect particles via, for example: radial transport with injections from the magnetotail and ultra low frequency waves, local heating and loss into Earth's atmosphere due to wave-particle interactions [Cite Ripoll et al., 2019 "Particle Dynamics in the Earth's Radiation Belts: Review of Current Research and Open Questions"](#). Whistler mode chorus (WMC) is just one type of plasma wave characterized by short (≈ 100 ms) rising tone elements, and perform a dual role in electron dynamics: accelerating electrons from ≈ 10 keV injection energies up to MeV energies, and pitch angle scattering electrons into the atmosphere (e.g. Li, Thorne, Angelopoulos, Bonnell, et al., 2009; Thorne, 2010; Horne & Thorne, 2003; Summers, 2005). One form of electron precipitation is microbursts: a transient and intense increase of electrons, with a ≈ 100 ms duration, first observed by balloons in Earth's upper atmosphere, and later by satellites in low Earth orbit (LEO), and recently at high altitude near the magnetic equator (e.g. Anderson & Milton, 1964; Blake et al., 1996; Lorentzen et al., 2001; O'Brien et al., 2003; Douma et al., 2017; Kurita et al., 2016; Shumko et al., 2018).

Rewrite sentence. → The observed microburst electron energies span multiple orders of magnitude from tens of keV observed by, for example, Datta et al. (1997) to > 1 MeV observed by, for example, the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) by Blum et al. (2015). Spatially, microbursts are predominately observed outside the plasmopause; on the radiation belt footprints, $L \approx 4-8$; and in the morning Magnetic Local Time (MLT) (0-12 hours MLT) (Lorentzen et al., 2001; Blum et al., 2015; O'Brien et al., 2003; Douma et al., 2017). **If keeping the AE plot, discuss the microburst occurrence as a function of AE and Dst (Emma's and Paul's work).**

Talk about their impact on the environment

Electron microbursts and chorus waves were associated early on, due to their similar duration and similar occurrence distributions in MLT (e.g. Lorentzen et al., 2001). Recently, Breneman et al. (2017) directly linked a chorus rising tone element to a microburst observed by the Focused Investigation of Relativistic Electron Bursts: Intensity, Range, and Dynamics (FIREBIRD-II) CubeSats (Johnson et al., 2020) during a close magnetic conjunction. With this evidence, the particle precipitation community is largely in agreement that chorus waves scatter microbursts. A natural follow-on question is how. For example, it is still unclear if relativistic (> 1 MeV) microbursts are scattered via cyclotron resonance at high magnetic latitudes, or a higher resonance harmonic near the magnetic equator (Lorentzen et al., 2001). One way to address this question is by studying for how long microburst electrons are in resonance with a chorus wave. The resulting microburst duration, i.e. the microburst peak width in the time series data, is a probe into the conditions necessary to scatter microburst electrons. From our literature review, we found only qualitative estimates of the microburst duration. Therefore, we used the microbursts observed by the SAMPEX satellite to quantify the distribution of > 1 MeV microburst duration. In this letter, we investigated the duration distribution as a function of: L-shell, MLT, and the Auroral Electrojet.

2 Instrumentation

Outline

1. Describe SAMPEX
2. Describe HILT
3. Describe the 20 ms data used in this study (State4, 20 ms, avoided spin times).
Data duration.

In this study we used the > 1 MeV electron count data, taken by the Heavy Ion Large Telescope (HILT) instrument (Klecker et al., 1993), that was onboard the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) satellite (Baker et al., 1993).

SAMPEX was launched in July 1992 and reentered Earth's atmosphere in November 2012. It was in a 520x670 km, 82° inclination low Earth orbit. Broadly, the SAMPEX had two pointing modes: spin mode and zenith pointing modes. To avoid the compounding effects due to the variable pitch angles sampled in the spin mode, we focused this study on the zenith pointing data.

We used the 20 ms HILT data (state4 in the data archive), taken between 1997 and 2012.

3 Methodology

To estimate the microburst duration we first identified microbursts and then we fit them with a Gaussian model with a linear trend to quantify the duration for each microburst.



Figure 1. Example > 1 MeV microbursts shown by the black lines, and the fits shown by the dashed red lines. The fit full width at half maximum (FWHM) and the \bar{R}^2 goodness of fit metric is annotated in each panel. Microbursts with $\bar{R}^2 > 0.9$ were used for this study. The major time ticks are at every second, while the minor ticks are at every 100 milliseconds.

3.1 Microburst Identification

We identified microbursts using the burst parameter defined by O’Brien et al. (2003) and used in numerous other microburst studies with SAMPEX (e.g. Douma et al., 2017). Assuming Poisson probability for the observed electron counts, the burst parameter is the number of standard deviations of a foreground signal above the background, expressed as

$$n_{\sigma} = \frac{N - A}{\sqrt{A + 1}} \quad (1)$$

Find a better variable than bp. This is not British Petroleum where N is the number of foreground electron counts (microburst or otherwise), and A is the centered running average background counts. The 1 in the denominator prevents a division by 0 error. In O’Brien et al. (2003), and in the results in this study, N was summed over 0.1 seconds and is called N_{100} , while A was summed over 0.5 seconds and is called A_{500} . Henceforth we will specify the time window with the subscript for N and A . Times when $bp > 10$ are classified as microburst times, and the peak count rate in each time interval is saved as a microburst to our data set. With A_{500} and N_{100} , we detected a total of 256,764 microbursts over the 13 year period from 1997 to 2012. Four examples of microbursts are shown in Fig. 1 by the solid black curves.

Check the argument for clarity The choice of A determines the sensitivity of the burst parameter to microbursts of various durations (widths). This sensitivity is best illustrated with an example. Given a 1-second wide microburst, if we use A_{500} , the centered average background at the microburst time is skewed towards the microburst peak and the microburst’s bp is reduced, potentially below the detection threshold. On the other hand, if we use A_{1000} , the centered running background will be relatively less elevated at the microburst time so it has a greater bp and is more likely to be detected. In other words, bp will be relatively larger for A_{1000} than A_{500} . This sensitivity manifests itself as a bias towards detecting narrower microbursts that we will address later in this study.

3.2 Microburst Duration

We estimated the microburst duration using two methods that yielded similar results: the duration at half of the microburst’s topographic prominence and duration from a Gaussian fit.

The topographic prominence is a simple and robust method to estimate the microburst duration used to identify curtains a similar-looking type of precipitation (Shumko et al., 2020) **Fix citation once paper is published**. It is defined as the duration at half of the microburst topographic prominence: the height of the microburst relative to the maximum of the two minima on either side of the microburst peak. On each side of the microburst peak, the minima are searched for between the microburst and a higher peak on that side. While the topographic prominence method of estimating microburst durations is simple and robust, one of its downsides is its inability to automatically verify that the duration is representative of a single microburst. Therefore, we also fit microbursts with a Gaussian, and used the R^2 goodness of fit metric to filter out bad duration estimates.

The other method that we use to estimate the microburst duration is fitting a Gaussian shape to microbursts. The advantage of this method is that it allows us to evaluate the fit using a goodness of fit metric. By screening out bad fits, we exclude superposition of multiple microbursts that will unintentionally bias our microburst duration estimate.

We assumed a Gaussian superposed with a linear trend fit model. The Gaussian models the shape of the microburst; while the linear trend accounts for the electrons that are either trapped or quasi-trapped in the drift loss cone. The fit model is defined as:

$$c(t|A, t_0, \sigma, c_0, c_1) = Ae^{-\frac{(t-t_0)^2}{2\sigma^2}} + c_0 + c_1t \quad (2)$$

where A , t_0 , and σ are the Gaussian amplitude, center time, and standard deviation; while the c_0 and c_1 are the background count intercept and slope. The fit was applied over a number of data points determined by the maximum of either: 4x topographic prominence width or 0.5 seconds. A challenge to any robust and automated nonlinear regression algorithm is guessing the initial parameters. The initial parameter guesses for the Gaussian are provided by the topographic prominence and topographic duration estimates. The two linear trend initial parameters were: $c_0 = 50$ and $c_1 = 0$. The optimal fit parameters were found using scipy's `curve_fit()` function in Python. We defined the microburst duration as the full width at half maximum (FWHM) of the microburst peak, defined as

$$\text{FWHM} = 2\sqrt{2 \ln 2} \sigma. \quad (3)$$

To evaluate the fit, we used the R^2 goodness of fit metric. R^2 is defined as

$$R^2 = 1 - \frac{SS_{res}}{SS_{total}} = 1 - \frac{\sum (c_i - f_i)^2}{\sum (c_i - \bar{c})^2} \quad (4)$$

where SS_{res} is the sum of squares of the residuals between the observed counts c_i and the fit counts f_i for each time stamp, and SS_{total} is the sum of squares between c_i and the mean counts \bar{c} .

One interpretation of R^2 is: fractionally how much better the variance in the data is explained by the model fit, compared to the null hypothesis horizontal line at \bar{c} . When $R^2 = 1$, the modeled fit perfectly describes the variance in the data, and R^2 can be arbitrarily negative for poor fits (a fit can be much worse than the mean).

To account for overfitting that results from the variable number of data points used for each fit, the adjusted R^2 , \bar{R}^2 , was used. It is defined as

$$\bar{R}^2 = 1 - (1 - R^2) \frac{n - 1}{n - p - 1} \quad (5)$$

where n is the number of data points fit, and p is the number of parameters. Intuitively, $n - 1$ is the number of degrees of freedom for the null hypothesis, and $n - p - 1$ is the



Figure 2. The distribution of all microburst full width at full maximum (FWHM). *Maybe merge this plot with the AE plot?*

degrees of freedom for the fit model. Fits with $\bar{R}^2 > 0.9$ are considered good fits and are used for the rest of this analysis. We compared the microburst duration estimated with the prominence and fit methods. With the $\bar{R}^2 > 0.9$ constraint, we found that for 85% of microbursts, the duration estimated by both methods agreed to within 25%.

Figure 1a shows an example of two superposed microbursts that had a fit $\bar{R}^2 = 0.83$ that were excluded from this study. On other hand, Fig. 1b-d show microbursts that were included in this study because the fit $\bar{R}^2 > 0.9$.

Lastly, Fig. 1c,d demonstrate the necessity of the linear fit to account for the changing background. The linear fit accounts for the non-zero mean background counts and the different amplitudes of the edges of the Gaussian. Of the 256,764 detected microbursts, 109,231 had $R^2 > 0.9$ and are used for the remainder of this study.

4 Results

The well-fit microbursts are used to quantify the distribution of microburst duration (FWHM) for all microbursts, as a function of L and MLT, and as a function of the Auroral Electrojet (AE). We begin with the overall microburst distribution.

Figure 2 shows the distribution of all well-fit microbursts. This distribution is peaked with the median at 98 ms and quickly drops off. The interquartile range spans about a factor of two in microburst duration, from 67 to 140 ms.

Figure 3 shows the joint distribution of microburst duration as a function of L and MLT. Figure 3a-c show the 25%, 50%, and 75% percentiles of microbursts in each L-MLT bin. The sparse bins with less than 100 well-fit microbursts are white. For reference, Fig. 3d shows the number of well-fit microbursts observed as a function of L and MLT.

In Fig. 3, the microburst duration trend is almost identical for the different percentiles, but let's focus on the median distribution, Fig. 3b. In MLT, the median microburst duration increases by a factor of two: from 80 ms at midnight to 160 ms at noon. In L-shell, the median microburst duration slightly increases with L shell, most apparent near midnight MLT. To disentangle the L and MLT distribution, Fig. 4 shows the marginalized distributions; MLT was marginalized out in Fig. 4a and L-shell was marginalized out in Fig. 4b. Figure 4a shows a slight broadening of the microburst duration at higher L-shells; in contrast to Fig. 4b that clearly shows that the microburst duration increases from midnight to noon MLT.

Lastly, we investigated the dependence of microburst duration as a function of geomagnetic activity. To be consistent with the prior wave and microburst studies, we use the Auroral Electrojet (AE) index to quantify the level of geomagnetic disturbance. We adopt the same three AE intensity levels used in prior studies, such as Li, Thorne, Angelopoulos, Bortnik, et al. (2009), Douma et al. (2017), and Meredith et al. (2020): $AE < 100$, $100 < AE < 300$, and $300 < AE < 1000$, in nanotesla units. Figure 5 shows the distribution of microburst duration as a function of AE. This distribution is similar across the three AE intensity levels. However, the distribution is more prominently peaked at 0.1 s at the highest intensity level.

5 Discussion and Conclusions

Outline

1. Compare to prior microburst width estimates.
2. Comment that microbursts at lower energy are wider (data + model). The cited microburst widths are dependent by the energy channel of the instrument.
3. Compare to chorus rising tone element duration trends.
4. A few concluding remarks.

To address the burst parameter preferential bias to narrower microbursts, as introduced in section 3.1, we ran the microburst identification algorithm on the data using three background values: A_{500} , A_{1000} , and A_{1000} . As described in section 3.1, an detection algorithm who's centered running average is over wider time periods will be more sensitive to wider and less prominent microbursts. Therefore we can identify the bias if there is a relative excess of longer duration microbursts when the average time was increased. We found no such excess for microburst data sets that were made using A_{1000} , and A_{1000} . Therefore, we believe that > 1 MeV microbursts are truly narrower than 250 ms and the A_{500} is adequate to identify > 1 MeV microbursts.

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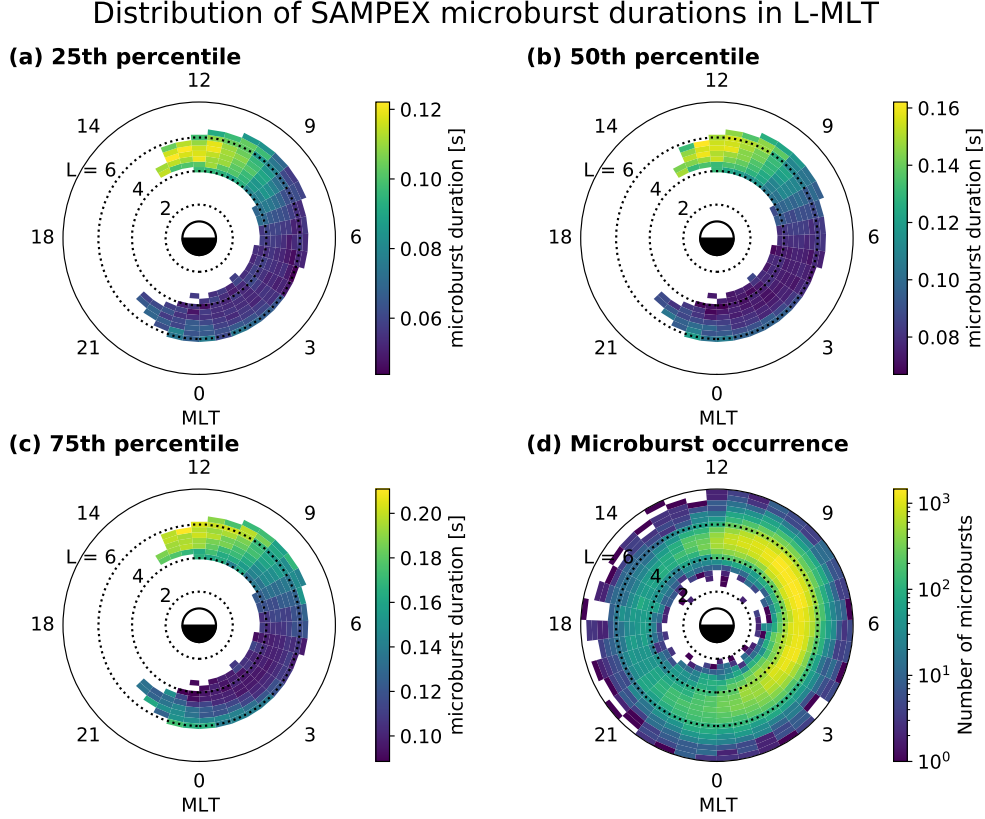


Figure 3. The joint distributions of microburst duration (FWHM) as a function of L and MLT. In each L-MLT bin with more than 100 good microburst fits, the 25th, 50th, and 75th percentiles of the duration were calculated and shown in panels a-c, respectively. The white bins in panels a-c have less than 100 good microburst fits. Panel d shows the distribution of the number of microbursts with 0 microbursts shown with the white bins.

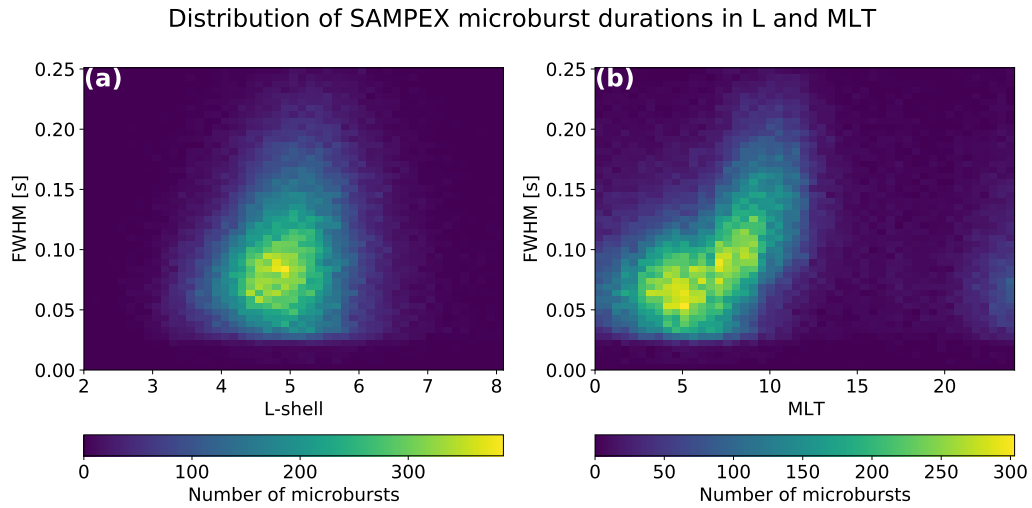


Figure 4. The marginalized distributions of the number of microbursts as a function of microburst duration (FWHM) and L shell in panel a and MLT in panel b.

Distribution of >1 MeV microburst duration as a function of AE

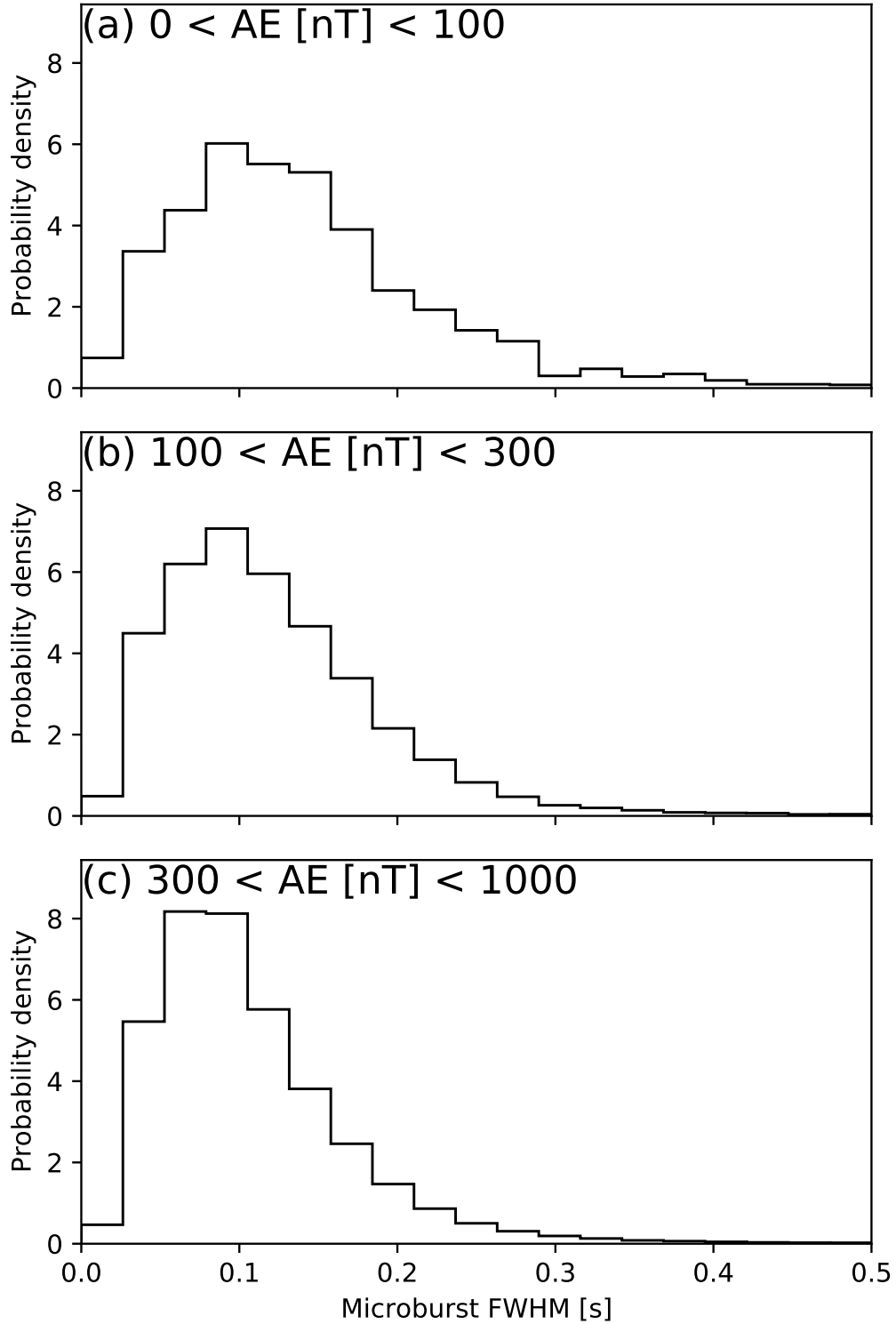


Figure 5. The distribution of the microburst duration (FWHM) for three ranges of the Auroral Electrojet: $\text{AE} < 100$, $100 < \text{AE} < 300$, and $300 < \text{AE} < 1000$ nT in Panels a-c, respectively. The x- and y-axis share identical limits between the three panels.

References

- Anderson, K. A., & Milton, D. W. (1964). Balloon observations of X rays in the auroral zone: 3. High time resolution studies. *Journal of Geophysical Research*, 69(21), 4457–4479. Retrieved from <http://dx.doi.org/10.1029/JZ069i021p04457> doi: 10.1029/JZ069i021p04457
- Baker, D. N., Mason, G. M., Figueroa, O., Colon, G., Watzin, J. G., & Aleman, R. M. (1993). An overview of the solar anomalous, and magnetospheric particle explorer (SAMPEX) mission. *IEEE Transactions on Geoscience and Remote Sensing*, 31(3), 531–541.
- Blake, J. B., Looper, M. D., Baker, D. N., Nakamura, R., Klecker, B., & Hovestadt, D. (1996). New high temporal and spatial resolution measurements by sampex of the precipitation of relativistic electrons. *Advances in Space Research*, 18(8), 171 - 186. Retrieved from <http://www.sciencedirect.com/science/article/pii/0273117795009698> doi: [http://dx.doi.org/10.1016/0273-1177\(95\)00969-8](http://dx.doi.org/10.1016/0273-1177(95)00969-8)
- Blum, L., Li, X., & Denton, M. (2015). Rapid MeV electron precipitation as observed by SAMPEX/HILT during high-speed stream-driven storms. *Journal of Geophysical Research: Space Physics*, 120(5), 3783–3794. Retrieved from <http://dx.doi.org/10.1002/2014JA020633> (2014JA020633) doi: 10.1002/2014JA020633
- Breneman, A., Crew, A., Sample, J., Klumpar, D., Johnson, A., Agapitov, O., . . . others (2017). Observations directly linking relativistic electron microbursts to whistler mode chorus: Van allen probes and FIREBIRD II. *Geophysical Research Letters*.
- Datta, S., Skoug, R., McCarthy, M., & Parks, G. (1997). Modeling of microburst electron precipitation using pitch angle diffusion theory. *Journal of Geophysical Research: Space Physics*, 102(A8), 17325–17333.
- Douma, E., Rodger, C. J., Blum, L. W., & Clilverd, M. A. (2017). Occurrence characteristics of relativistic electron microbursts from SAMPEX observations. *Journal of Geophysical Research: Space Physics*, 122(8), 8096–8107. Retrieved from <http://dx.doi.org/10.1002/2017JA024067> (2017JA024067) doi: 10.1002/2017JA024067
- Horne, R. B., & Thorne, R. M. (2003). Relativistic electron acceleration and precipitation during resonant interactions with whistler-mode chorus. *Geophysical Research Letters*, 30(10). Retrieved from <http://dx.doi.org/10.1029/2003GL016973> (1527) doi: 10.1029/2003GL016973
- Johnson, A., Shumko, M., Griffith, B., Klumpar, D., Sample, J., Springer, L., . . . others (2020). The FIREBIRD-II CubeSat mission: Focused investigations of relativistic electron burst intensity, range, and dynamics. *Review of Scientific Instruments*, 91(3), 034503.
- Klecker, B., Hovestadt, D., Scholer, M., Arbinger, H., Ertl, M., Kastele, H., . . . others (1993). HILT: A heavy ion large area proportional counter telescope for solar and anomalous cosmic rays. *IEEE transactions on geoscience and remote sensing*, 31(3), 542–548.
- Kurita, S., Miyoshi, Y., Blake, J. B., Reeves, G. D., & Kletzing, C. A. (2016). Relativistic electron microbursts and variations in trapped mev electron fluxes during the 8–9 october 2012 storm: Sampex and van allen probes observations. *Geophysical Research Letters*, 43(7), 3017–3025. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016GL068260> doi: <https://doi.org/10.1002/2016GL068260>
- Li, W., Thorne, R., Angelopoulos, V., Bonnell, J., McFadden, J., Carlson, C., . . . Auster, H. (2009). Evaluation of whistler-mode chorus intensification on the nightside during an injection event observed on the THEMIS spacecraft. *Journal of Geophysical Research: Space Physics*, 114(A1).
- Li, W., Thorne, R. M., Angelopoulos, V., Bortnik, J., Cully, C. M., Ni, B., . . .

- 299 Magnes, W. (2009). Global distribution of whistler-mode chorus waves ob-
300 served on the THEMIS spacecraft. *Geophysical Research Letters*, 36(9).
301 Retrieved from <http://dx.doi.org/10.1029/2009GL037595> (L09104) doi:
302 10.1029/2009GL037595
- 303 Lorentzen, K. R., Blake, J. B., Inan, U. S., & Bortnik, J. (2001). Observations of
304 relativistic electron microbursts in association with VLF chorus. *Journal of*
305 *Geophysical Research: Space Physics*, 106(A4), 6017–6027. Retrieved from
306 <http://dx.doi.org/10.1029/2000JA003018> doi: 10.1029/2000JA003018
- 307 Meredith, N. P., Horne, R. B., Shen, X.-C., Li, W., & Bortnik, J. (2020). Global
308 model of whistler mode chorus in the near-equatorial region ($|\lambda_m| < 18^\circ$). *Geo-*
309 *physical Research Letters*, 47(11), e2020GL087311.
- 310 O’Brien, T. P., Lorentzen, K. R., Mann, I. R., Meredith, N. P., Blake, J. B., Fen-
311 nell, J. F., ... Anderson, R. R. (2003). Energization of relativistic elec-
312 trons in the presence of ULF power and MeV microbursts: Evidence for dual
313 ULF and VLF acceleration. *Journal of Geophysical Research: Space Physics*,
314 108(A8). Retrieved from <http://dx.doi.org/10.1029/2002JA009784> doi:
315 10.1029/2002JA009784
- 316 Shumko, M., Johnson, A. T., O’Brien, T. P., Turner, D. L., Greeley, A. D., Sam-
317 ple, J. G., ... Halford, A. J. (2020). Statistical properties of electron cur-
318 tain precipitation estimated with aerocube-6. *Journal of Geophysical Re-*
319 *search: Space Physics*, n/a(n/a), e2020JA028462. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020JA028462)
320 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020JA028462
321 (e2020JA028462 2020JA028462) doi: <https://doi.org/10.1029/2020JA028462>
- 322 Shumko, M., Turner, D. L., O’Brien, T. P., Claudepierre, S. G., Sample, J.,
323 Hartley, D. P., ... Mitchell, D. G. (2018). Evidence of microbursts ob-
324 served near the equatorial plane in the outer van allen radiation belt. *Geo-*
325 *physical Research Letters*, 45(16), 8044-8053. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL078451)
326 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL078451 doi:
327 10.1029/2018GL078451
- 328 Summers, D. (2005). Quasi-linear diffusion coefficients for field-aligned electro-
329 magnetic waves with applications to the magnetosphere. *Journal of Geophys-*
330 *ical Research: Space Physics*, 110(A8), n/a–n/a. Retrieved from [http://](http://dx.doi.org/10.1029/2005JA011159)
331 dx.doi.org/10.1029/2005JA011159 (A08213) doi: 10.1029/2005JA011159
- 332 Thorne, R. M. (2010). Radiation belt dynamics: The importance of wave-particle in-
333 teractions. *Geophysical Research Letters*, 37(22). Retrieved from [http://dx](http://dx.doi.org/10.1029/2010GL044990)
334 [.doi.org/10.1029/2010GL044990](http://dx.doi.org/10.1029/2010GL044990) (L22107) doi: 10.1029/2010GL044990