Understanding the properties, wave drivers, and impacts of electron microburst precipitation: current understanding and critical knowledge gaps

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Abstract/Synopsis

Microbursts are impulsive (~100ms) injections of very energetic to relativistic electrons (energies from a few keV to MeV) into Earth's atmosphere. Microbursts are important because they may represent a major loss process for the outer radiation belt (*Ripoll et al., 2020*). Understanding and quantifying the underlying causes and consequences plus relative importance of microburst precipitation represent outstanding questions in radiation belt physics and may have significant implications ranging from space weather to atmospheric chemistry. Chorus waves are the likely dominant cause of microburst precipitation, but important questions remain regarding the exact nature of the resonance generating the microbursts and the overall importance of the precipitation. These important questions are limited by lack of systematic coordination of simultaneous observations of causative waves in the magnetosphere and resulting precipitating particles at low altitudes. Increased funding for multi-spacecraft missions dedicated to answering these questions is critical.

Introduction/Background

Many competing processes contribute to the formation and depletion of Earth's radiation belts (see reviews by *Thorne, 2010; Millan and Thorne, 2007; Ripoll et al, 2020*). The outer radiation belt is highly dynamic, as many competing energization, loss and transport processes occur simultaneously and are energy dependent. Understanding and quantifying the importance of each process is fundamental to radiation belt physics and has significant implications ranging from human space flight (*Lanzerotti and Baker, 2017*) to space weather forecasting and atmospheric chemistry (*Andersson et al., 2014; Mironova et al., 2015; Meredith et al., 2017*) and even climatology (e.g. *Seppala et al., 2014; Matthes et al., 2017*).

Microbursts are impulsive (<1s) injections of energetic (few keV to MeV) electrons into the atmosphere. They are important because they may represent a major loss mechanism from the outer radiation belt during storm main and recovery phases (*O'Brien et al., 2004; Thorne et al.*, 2005; *Millan and Thorne, 2007*). Low energy (10s of keV) microburst precipitation has been observed since the 1960s via balloon measurements of bremsstrahlung X-rays produced by precipitating electrons when they enter Earth's atmosphere (*Anderson and Milton, 1964; Winckler et al., 1962; Millan et al, 2002*). Microbursts at higher energies (>100s keV) have also been observed on satellites (*Blake et al., 1996; Imhof and Nightingale, 1992*). Figure 1 (from *Lorentzen et al., 2001)* shows observations of >1 MeV electron flux taken by the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) satellite, demonstrating that although the microbursts are short-lived, they can have fluxes more than an order of magnitude higher than the background precipitation. Therefore, microburst precipitation has the potential to be a significant loss mechanism for outer radiation belt energetic electrons.

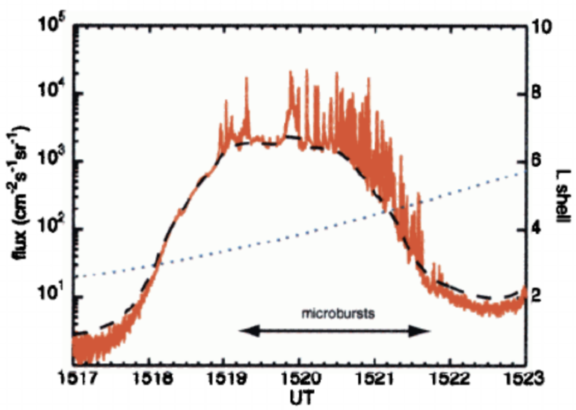

Figure 1. Electron microburst observations from Lorentzen et al., 2001. Electrons >1 MeV microbursts observed on October 19, 1998 (red). Estimate of the locally trapped population (black). L-shell position of satellite (blue).

Recent studies have also suggested that relativistic electron microbursts are the high-energy tail of pulsating aurora (*Miyoshi et al., 2020*), and a high correlation between patchy aurora (a type of pulsating aurora) and >1 MeV microbursts was found by *Shumko et al. (2021a)*. Figure 2 shows an example of concurrent pulsating aurora and relativistic electron microbursts. *Jones et al. (2013)* analyzed a pulsating auroral event with a duration of >15 hours with an extent larger than 10 hours in MLT, indicating that these aurora events are more significant than previously predicted. These studies suggest electron microbursts have important implications for magnetosphere-ionosphere coupling and, in turn atmospheric composition. Seppala et al. [2018] modeled a 6-hour microburst 'storm' with typical characteristics and found that this precipitation significantly altered NOx and HOx, resulting in a >10% decrease in both middle mesospheric and upper mesospheric ozone, which has implications for regional weather. Additionally, the aurora is a universal process observed on other planets such as Jupiter. Further understanding of energetic particle precipitation at Earth will aid in interpretation of similar processes in different plasma regimes. Despite a long history of observations, the detailed physics of the underlying scattering mechanism and the relative importance of microburst precipitation as a loss mechanism for outer belt energetic electrons is poorly understood (see review by *Blum and Breneman, 2020; Breneman et al., 2017, Douma et al., 2019*).

To date, strong evidence suggests that the dominant cause of microburst precipitation is through resonant wave-particle interactions with whistler mode chorus waves (*Nakamura et al., 2000; Lorentzen et al., 2001; Breneman et al., 2017, Colpitts et al., 2020*). Electromagnetic ion cyclotron (EMIC) waves are another type of plasma wave that can scatter electrons (typically in the MeV energies) through anomalous cyclotron resonant interactions (*Thorne and Kennel, 1971*). Studies (e.g. *Capannolo et al.,* 2021) have shown evidence that EMIC wave precipitation may extend to lower energies in the hundreds of keV range and only recently has evidence of EMIC-driven microburst precipitation been discovered (*Shumko et al., 2022)*. Therefore, investigating resonant interactions with EMIC waves is important in the overall understanding of microburst precipitation. Although chorus is the likely dominant driver of microbursts, **many details regarding the scattering process, including the latitude where the interaction takes place and the exact nature of the resonance, remain unverified or unknown**. Additionally, direct causation has only been shown in limited cases (e.g. *Breneman et al., 2017*). **Furthermore, basic details of microbursts that are necessary to ascertain their significance as a loss mechanism including duration, isotropy, repetition, and temporal versus spatial variability are still largely unknown** (e.g. *Shumko et al., 2021b*). The reason why these unanswered questions exist is largely due to lack of simultaneous observations of microbursts and waves over a large region and extended period of time.

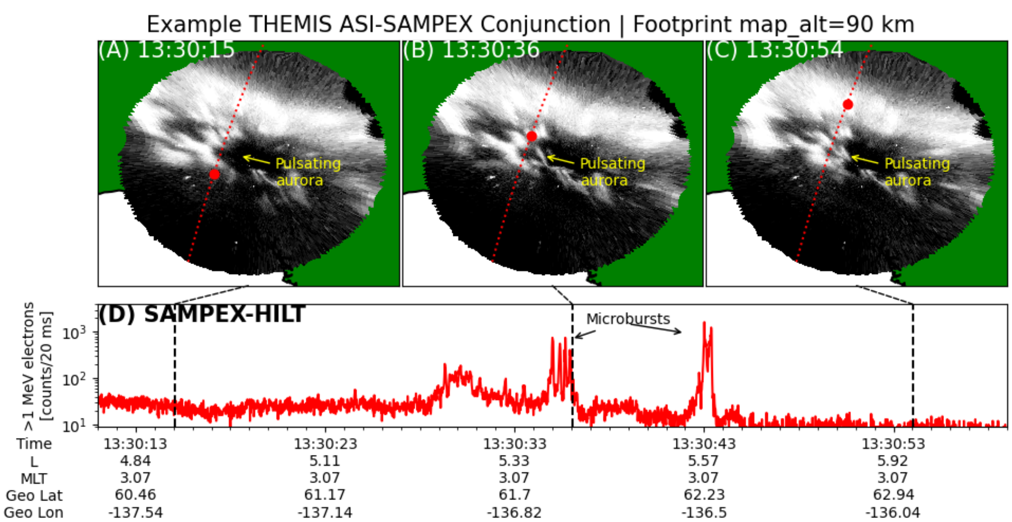

Figure 2. An example THEMIS ASI-SAMPEX conjunction with concurrent pulsating aurora and relativistic microbursts. Panels (A-C) show auroral images projected onto a geographic map. Superposed on the map are the full and instantaneous SAMPEX satellite footprints, shown by the red dotted line and circle, respectively. Panel (D) shows the >1 MeV electron precipitation observed by the HILT instrument onboard SAMPEX. Microbursts were clearly observed between 13:30:33-13:30:43 while SAMPEX passed through pulsating aurora patches. The minor ticks are at every second.

Recently, studies utilizing a conjunction dataset of high-altitude chorus wave observations made on Van Allen Probes (RBSP) and microburst observations on the low-altitude Focused Investigations of Relativistic Electron Burst: Intensity, Range, and Dynamics (FIREBIRD) CubeSats have unveiled details of the connection between chorus and microbursts. *Breneman et al. (2017)* used a conjunction event to prove the chorus/microburst connection, but even so this event only led to a very uncertain estimate of the importance of microbursts as a loss mechanism. **The relative importance of microbursts as a loss process cannot be fully constrained without accurate measurements of the flux of microbursts through a given area over a given amount of time.** Obtaining accurate measurements requires very good temporal resolution, energy resolution, and angular resolution, the combination of which is extremely challenging for existing instrument technology. Future missions focused on addressing this question are needed to enable an accurate determination of the loss due to microbursts compared to the overall loss from the radiation belts. Furthermore, missions focused on the properties and extents of various plasma waves and their effects on energetic electrons in the inner magnetosphere are necessary to fully understand microburst precipitation.

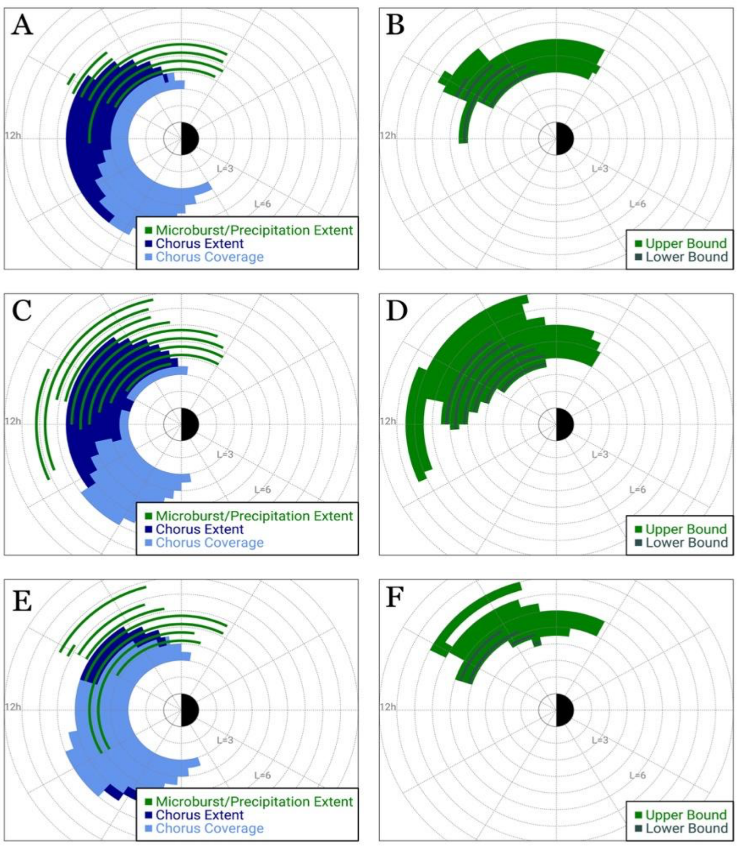

Figure 3. From Elliott et al. (2022) showing chorus observations from RBSP, Arase, and ground-based VLF stations, and microburst precipitation from FIREBIRD, AeroCube-6, and POES. (a,c,e) Overview of three periods of persistent chorus and microburst precipitation observations. Green bars represent of microburst precipitation extent between 4 and 14 MLT. Dark blue bars show the chorus extent. Light blu blue bars show the chorus coverage. (b,d,f) Upper (green) and lower (gray) bounds on the size of the microburst-producing chorus region. Green bars include regions where chorus and microburst precipitation are observed and regions where only microbursts are observed but no chorus waves due to lack of coverage.

Another area that needs further investigation is how chorus wave properties, which change with geomagnetic activity and location, affect the wave-induced precipitation. These properties are important for estimates of diffusion coefficients, which would be valuable for modeling long-term dynamics of radiation belts due to wave-particle interaction. The morphology of these wave regions is also important for understanding the significance of microburst precipitation. A recent study by *Elliott et al. (2022)* combined observations of chorus and microburst precipitation from nearly all available satellite-borne and ground-based data to estimate the typical size and duration of a microburst precipitation region. Even in this best-case scenario of available observations, significant assumptions were required regarding the continuity of chorus between two observational points. In addition, substantial gaps were existing in regions of the magnetosphere due to lack of spacecraft observations. Figure 3 (from *Elliott et al., 2022)* shows the microburst precipitation and chorus extent for three intervals. Regions of overlap between the chorus wave and microburst precipitation observations were used for the lower estimates. There were regions where microbursts were observed, but there was no spacecraft coverage to detect chorus waves. This study highlights the critical need for constellation missions studying the wave properties along with particle measurements in order to determine where wave-particle interactions can occur, which particle energies resonate with the waves, and the dependence of these regions on geomagnetic activity. Additionally, there exists a latitude gap of missing data between the equatorial source region of chorus waves and the regions where the scattering occurs.

Science Priorities and Path to Successful Understanding of Microburst Precipitation by Waves

Important questions remain on microburst precipitation by waves in the inner magnetosphere, including, but not limited to, the exact nature of the resonance generating the microbursts, including the extent of the resonance region off the equator, and the overall importance microburst precipitation has on radiation belt electron loss. These gaps in our understanding largely exist due to the sparseness of simultaneous observations of waves and particles. Equatorial satellites are ideal for measuring in situ wave populations, such as chorus, generated near the equator. However, these satellites are typically unable to resolve electrons in the loss cone. In a similar vein, low Earth orbiting satellites, like FIREBIRD, are able to directly observe microburst precipitation, but are far away from the wave source region. This makes direct testing of microburst generation very difficult due to the large separation over which the waves and microbursts are observed. The current state of knowledge is therefore limited to multipoint observations and magnetic conjunctions between satellites.

The following are a list of science goals that we recommend for the upcoming decade. While some goals can be achieved using existing datasets, other goals need dedicated space-based instrumentation.

1) **Improve our understanding of how/where plasma waves generate energetic electron microburst precipitation.**

   - Continued support of projects that investigate multipoint observations of waves and microburst precipitation is important to make incremental, important steps towards our understanding of the generation mechanisms for microbursts. We recommend increased funding and support for modeling, including ray tracing and test particle simulations, which will help us understand the details of the scattering process. Recent studies (e.g. *Colpitts et al., 2020; Chen et al. 2020; Miyoshi et al. 2020; Chen et al. 2022*) used ray tracing simulations and satellite observations to show direct evidence of chorus elements propagating from the equator to higher latitudes where microbursts can be produced. This was an important step towards understanding this fundamental radiation belt physics question. However, the flux of microbursts through a given area in a given amount of time remains unknown and is necessary to quantify the contribution of this process to radiation belt loss. We therefore recommend a mission with both an imager and a particle detector, which could directly measure the particles while imaging a significant sector of the precipitation region in order to quantify the flux and spectrum of microburst precipitation throughout the region. In addition, constellation missions dedicated towards answering these questions are critical. Therefore, we recommend a mission focused on making measurements of both waves and particles along magnetic field lines from where the waves are generated near the magnetic equator, up to higher latitudes. This type of mission would therefore be able to probe the structure of the waves and the impact they have on the particle populations. Additionally, a mission of this extent would be able to identify where the microbursts are generated and the wave properties responsible, which would significantly constrain the spatial and temporal scale of microburst precipitation.

2) **Further constrain the importance of microburst precipitation as a loss mechanism for outer belt energetic electrons.**

   - The importance of microburst precipitation relative to other radiation belt loss processes has yet to be established. *Breneman et al. (2017)* estimated from FIREBIRD microburst data the differential flux loss rate to the atmosphere due to microbursts. This was then used to estimate the amount of time it would take for this mechanism to deplete the entire outer radiation belt and therefore compare to other loss rates to determine the relative importance of microburst precipitation. However, the differential flux loss rate is poorly constrained and accurate measurements of the microburst flux within a given area over a given amount of time are required. Therefore, we recommend a mission dedicated to measuring the spatial distribution and energy spectrum of precipitating electrons, including microbursts. To further complicate things, there are other competing mechanisms for radiation belt electron loss, including magnetopause shadowing (e.g. Staples et al., 2022; Tu et al., 2019), therefore making it difficult to separate and quantify the relative importance of each. Improved measurement capabilities, including good temporal resolution, energy resolution, and angular resolution are needed. We also recommend constellation missions, including multipoint observations at low Earth orbit and wave and particle measurements along field lines at varying latitudes. This would provide wave and particle measurements near where the scattering is occurring in an effort to fully understand the overall importance of microburst precipitation.

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