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Fast Non-Equilibrium Pitch Angle Diffusion in a Plasmaspheric Plume Associated with BARREL Precipitation

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Abstract

This summary paper reports progress on an ongoing investigation of radiation belt electron pitch-angle scattering by plume hiss waves. We further analyze an electron precipitation event observed by BARREL, first reported in [1]. We find that the bremsstrahlung x-ray spectrum observed by BARREL is not consistent with an exponential precipitating electron energy spectrum, and is harder than the trapped electron spectrum measured by Van Allen Probes. We extend our quasi-linear diffusion model to consider a more realistic initial electron energy spectrum. The evolution of the electron phase space density towards a harder energy spectrum is qualitatively consistent with the BARREL observations and is attributed to the rapid loss of low energy particles at early times during their non-equilibrium interaction with the plume hiss waves.

1 Introduction

Whistler-mode hiss waves are a major driver of loss in the radiation belts (see review in [2]). These waves are frequently observed in plasmaspheric plumes by the twin Van Allen Probes spacecraft [3]. Recent work has shown that these low-frequency, broadband (~50 Hz-2 kHz) electromagnetic waves may also be an important driver of electron loss near the outer edge of the radiation belts due to their large electromagnetic power in plasmaspheric plumes [4, 5]. In this summary paper, we build on the work presented in [1] by further analyzing an electron precipitation event detected by BARREL. The bremsstrahlung x-rays produced by precipitating electrons were observed magnetically conjugate to plume hiss waves observed by the Van Allen Probes. To further investigate the energy spectrum of the precipitating electrons, we present the x-ray spectrum and a simple model of the x-ray emission. We also further explore the pitch-angle scattering of electrons by the plume hiss waves by expanding the event-driven quasi-linear diffusion model in [1] to include a more realistic initial electron distribution and to simulate the evolution of the spectrum in time.

2 Summary of Data and Methods

2.1 X-ray Observations

The BARREL (Balloon Array for Radiation belt Electron Loss) experiment was designed to measure bremsstrahlung x-rays produced by electrons precipitating into Earth's atmosphere from the radiation belts [6]. We previously reported detection of an x-ray burst by BARREL 3A on 10 August 2015 over Sweden [1]. The x-rays were attributed to precipitating electrons with energies primarily below 200 keV based on the lack of count rate increase at higher energies. The x-ray burst was observed in the region magnetically conjugate to the Van Allen Probes (RBSP) when they passed through a plasmaspheric plume. Intense whistler-mode hiss waves were observed by the EMFISIS instrument on each spacecraft in this high density region. We formerly argued that the plume hiss waves were responsible for scattering the electrons that produced the x-ray burst. Here we examine the observed x-ray spectrum in more detail to further investigate the energy of the precipitating electrons.

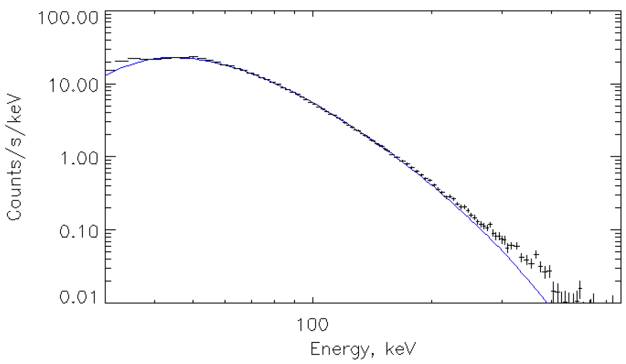

Figure 1. BARREL x-ray count spectrum (black) with model x-ray count spectrum (blue) superposed. The observed spectrum is harder than that expected for the best-fit model that assumes an exponential precipitating electron energy spectrum.

Figure 1 shows the background-subtracted x-ray count spectrum (black) averaged over the duration of the x-ray burst (15:30-17:30 UT) on 10 August 2015. Also shown (blue solid line) is a model x-ray spectrum as described below. The BARREL slow spectrum x-ray data product was used for this analysis [7]. The background spectrum was obtained by averaging over a 30-minute interval after the x-ray burst (1800-1830 UT). The x-ray background at balloon altitudes is due primarily to cosmic rays. The interval prior to the x-ray burst was not used because the balloon was still ascending during that time.

To produce the model x-ray count spectrum, we used the spectral modeling tools and response matrices provided by the BARREL project, made available as part of the SPEDAS software distribution [8]. The spectral modeling uses a forward-folding method and is described in detail in [7]. The response matrix provides the expected detector x-ray counts at each energy for a single electron with given initial energy incident on the top of the atmosphere. The response matrices are available for a range of different balloon altitudes and were produced using GEANT Monte Carlo simulations that include all relevant physics, including ionization losses, bremsstrahlung production, Compton scattering and photoelectric absorption of the x-rays in the atmosphere and detector mass model. The BARREL spectral modeling tool takes as input either a user-selected or a custom input energy distribution for the precipitating electrons. The output is a model x-ray count spectrum, produced by accumulation of the expected counts from the assumed distribution of incident electrons. The model x-ray spectrum is normalized to the observed BARREL spectrum to minimize the chi-square. For the user-selected inputs that contain a free parameter, the fit parameter is adjusted and a new model x-ray-spectrum and chi-square are computed. This process is iterated to provide a best-fit parameter that minimizes the chi-square. The model x-ray spectrum shown in Figure 1 is the best fit model x-ray count spectrum assuming an initial exponential distribution for the precipitating electrons ($exp(-E/E_0)$). The minimization algorithm comparing the model and observed x-ray spectra over the range 60-400 keV converges to a best-fit e-folding energy for incident electrons for which E_0 =98 keV. To sum up, the combination of the latter electron spectrum with BARREL response matrix provides the modeled x-ray counts (in blue in Figure 1). Comparing observed and modeled x-ray spectrum in Figure 1, we find the BARREL x-ray spectrum is harder than the best fit model x-ray count spectrum in this case, indicating an excess of higher energy precipitating electrons than would be expected for a simple exponential energy distribution.

An initial exponential precipitating electron distribution was chosen for the model here since the RBSP-B MagEIS flux data prior to the x-ray burst were well fit by an exponential with e-folding energy E_0 = 37 keV (see Figure 4b [1]). This comparison gives a feel for the energy range of electrons that produced the observed x-rays compared with the energy distribution of electrons in the radiation belts, though we immediately notice a difference in E_0 between the model and the RBSP observations. This calls for more accurately modeling the expected x-ray count spectrum to investigate how the electron spectrum may have evolved during the 2 hours of BARREL observation. The interaction of electrons with the plume hiss waves is expected to be energy-dependent and must be examined in more detail.

2.2 Quasi-linear Diffusion Model

We previously developed an event-driven quasi-linear diffusion model to investigate the interaction of radiation belt electrons with the observed plume hiss waves during the BARREL x-ray event [1]. The model incorporated observed wave properties, including mean frequency, frequency cut-offs, wave normal angle, and wave amplitude. Bounce-averaged diffusion coefficients were computed and the evolution of the electron phase-space density (PSD) was investigated by solving the Fokker-Planck equation (e.g. [9, 10, 11].

Figure 2 shows the time evolution of the electron PSD assuming an initial pitch angle distribution given by $\sin^b \alpha - \sin^b \alpha_{lc}$ where α is the pitch-angle, α_{lc} is the loss cone pitch-angle, and b is an energy-dependent parameter determined using RBSP MagEIS observations (see[1] for details). The top panel is reproduced from [1] and shows the result for each energy without any scaling for the energy distribution. The PSD, $f(t,E,\alpha)$, evolves from a normalized initial state. During the early times (e.g., 10 minutes for 135 keV), we observed a growth of the PSD which is due to the time that pitch-angle diffusion takes to start filling the loss cone, with a process that is controlled by non-equilibrium diffusion. The middle panel of Figure 2 shows the evolution of the PSD assuming an initial distribution that was scaled by the MagEIS observed energy spectrum at 1500 UT, $F_{MagEIS}(E)$. In that case the initial condition is $f_0(E) * (\sin^b \alpha - \sin^b \alpha_{lc})$ with $f_0 = F_{MagEIS}(E)/p(E)^2$ and $p(E)$ the electron momentum. At very early times, the energy spectrum near the loss cone edge is very similar to the initial energy spectrum. However, the energy-dependent diffusion coefficients cause the distribution to evolve differently at different energies, with a phase of growth during the first minutes. The lowest energies then decay more quickly, leading to a hardening of the spectrum at later times. The simulated electron flux spectrum is shown in Figure 2 (bottom panel) in which we reconstruct its evolution by time-integrating the simulated flux, $F(t,E,\alpha) = f(t,E,\alpha).p^2$, from $t = 0$ up to 10, 30 and 120 minutes. There is a progressive hardening due to the fast loss of electrons below $\sim$100 keV, due to the intense plume hiss. This result is qualitatively consistent with the BARREL observations which show a harder spectrum than that expected if one assumes for the electron distribution that the observed MagEIS distribution remains unchanged during BARREL's flight.

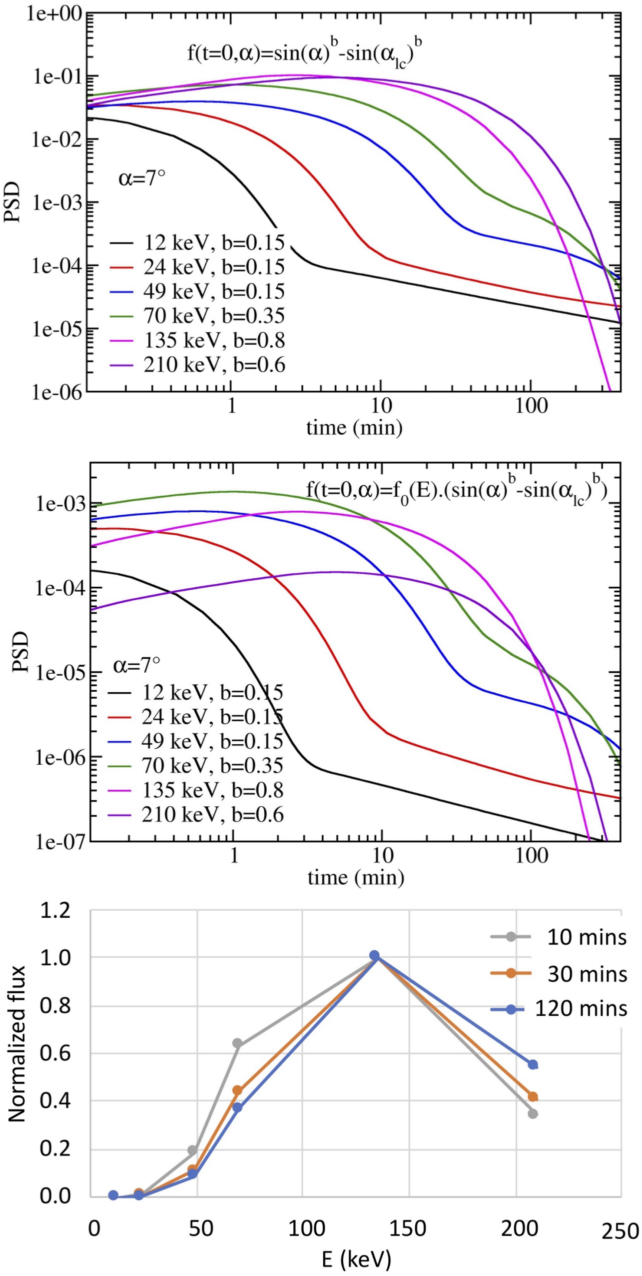

Figure 2. Evolution of the phase-space density at the loss cone edge for energies from 12 keV to 210 keV without (top) and with (center) the observed energy flux scaling. PSD growth can occur during the first 10 minutes and, then, the PSD starts decaying abruptly. Top figure is reproduced from Figure 9 in [1] for comparison. (bottom) Normalized flux spectrum reconstructed from the simulations shown in the center figure after 10, 30, and 120 minutes of integration.

3 Results and Discussion

In this paper, we build on the work presented in [1] by examining the observed x-ray spectrum produced by precipitating electrons during a BARREL event in August 2015. We further explore the evolution of the phase-space density and the expected evolution of precipitating electron energies due to interaction with plume hiss waves by incorporating a more realistic initial electron energy spectrum in the model. We find that the electron energy spectrum near and inside the loss cone should evolve in time and harden as the lower energy electrons are rapidly lost.

The results presented here provide a progress report and take the next steps towards producing a model x-ray spectrum using a dynamic electron spectrum extracted from a quasi-linear diffusion model. In order to accurately model the expected x-ray spectrum, the model will need to include the effects of energy-dependent gradient-curvature drift since higher energy (∼100 keV) electrons can drift across the plume in a few minutes, which also contributes to change the distribution. Future work will incorporate this to allow for a direct comparison of the model and observed spectra, providing the a more complete observational test of the model. Moreover, the x-ray spectrum presented above was averaged over the duration of the x-ray burst in order to improve the statistics. This study motivates future work to further examine the time evolution of both the electron and expected x-ray spectrum to determine whether any change in the precipitating electron spectrum over time, as expected from the quasi-linear diffusion model, can be detected by BARREL. We will also investigate how changes of the electron distribution due to substorm dynamics could influence the BARREL x-ray spectrum.

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