Inner radiation belt electron lifetimes due to whistler-induced electron precipitation (WEP) driven losses

Craig J. Rodger
Department of Physics, University of Otago, Dunedin, New Zealand

Mark A. Clilverd
Physical Sciences Division, British Antarctic Survey, Cambridge, United Kingdom

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[1] Wave-particle interactions driven by whistler mode waves in the inner Van Allan belt is an important loss process for the energetic electrons found in this region. In this paper we seek to investigate the significance of Whistler-Induced Electron Precipitation (WEP) to inner belt electron lifetimes, by combining experimental satellite results, ionospheric remote observations, and global lightning distributions. We find that long-term WEP driven losses at L = 2.23 are more significant than all other inner radiation belt loss processes for electron kinetic energies in the range 40–350 keV. This suggests a faster depletion rate and thus lower lifetimes than previously calculated. Thunderstorm generated whistlers are an important factor for determining the lifetimes of medium energy electrons in the inner belt. *INDEX TERMS:* 2716 Magnetospheric Physics: Energetic particles, precipitating; 2730 Magnetospheric Physics: Magnetosphere—inner; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2483 Ionosphere: Wave/particle interactions. **Citation:** Rodger, C. J., and M. A. Clilverd, Inner radiation belt electron lifetimes due to whistler-induced electron precipitation (WEP) driven losses, *Geophys. Res. Lett.*, *29*(19), 1924, doi:10.1029/2002GL015795, 2002.

1. Introduction

[2] It has been recognized for some time that the loss of radiation belt electrons in the inner magnetosphere is dominated by pitch angle scattering in wave-particle interactions with whistler mode waves and Coulomb collisions with atmospheric constituents. Coulomb collisions are the dominant loss process for energetic electrons (>100 keV) only in the inner-most parts of the radiation belts (L < 1.3). Beyond L $\sim$ 1.5 Coulomb collision-driven losses are generally less important than those driven by whistler mode waves, either through plasmaspheric hiss, whistlers, or manmade transmissions. Recent calculations suggest that all 3 may play an important role in the loss of energetic electrons from the inner magnetosphere [*Abel and Thorne*, 1998].

[3] Lightning-induced electron precipitation from the Van Allen radiation belts is a known troposphere to magnetosphere coupling mechanism. The energetic electron precipitation arises from lightning produced whistlers interacting with cyclotron resonant radiation belt electrons in the equatorial zone. Pitch angle scattering of energetic radiation belt electrons by whistler mode waves can drive these electrons into the bounce loss cone [*Walt*, 1994], and result in their precipitation into the atmosphere. Estimates of electron lifetimes due to Whistler-induced Electron Precipitation (WEP)-driven losses using ground-based whistler observations have assumed that the wave particle interaction takes place in narrow plasmaspheric ducts, such that each whistler only influences a small region of the radiation belts, creating an ionospheric patch that is small (370 km^2) [*Burgess and Inan*, 1993]. Due to the significant experimental uncertainties there has been disagreement between the results of such studies. While *Burgess and Inan* [1993] found that radiation belt losses driven by ducted whistlers might be comparable to those from plasmaspheric hiss, a similar study by *Smith et al* [2001] concluded that ducted whistlers were not significant in overall inner-belt losses. S81-1 satellite measurements have reported short bursts ($\sim$0.2 s) of magnetically guided and focused electrons in the bounce loss cone, primarily over $\sim$75 to $\sim$300 keV, correlated on a one-to-one basis with ground based observations of one-hop whistlers [*Voss et al.*, 1998]. Most recently, SAMPEX and UARS satellite data has revealed hundreds of cases where enhanced losses of 100–200 keV electrons were associated with individual thunderstorms [*Blake et al.*, 2001].

[4] A complementary technique to study WEP relies upon the ionospheric modifications produced by secondary ionization just below the D-region of the ionosphere. Ionospheric changes alter the propagation of very low frequency (VLF) waves trapped inside the Earth-ionosphere waveguide, and leads to perturbations in the amplitude and/or phase of narrow band subionospheric VLF transmissions, termed Trimpi perturbations. Until recently there was significant uncertainty as to the typical size of the D-region patch altered by WEP. Very recently Trimpi perturbations were used to determine that the ionospheric patch sizes caused by WEP were large (at least 600 km $\times$ 1500 km) [*Clilverd et al.*, 2002]. This study was unable to draw a definitive conclusion as to whether the whistlers leading to WEP (and hence Trimpi) were ducted or unducted, noting that either ducted or unducted whistlers can lead to large ionospheric patches [*Strangeways*, 1999; *Lauben et al.*, 1999]. The size of the ionospheric patches implies that the section of radiation belt influenced by each whistler must also be large. This will have a strong influence on estimates of the significance of WEP in radiation belt loss processes.

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[5] While the evidence for whistler induced precipitation is over-whelming, and the mechanisms behind WEP are well understood, the over all significance of WEP on radiation belt loss rates has not been clear. In this paper we seek to investigate the significance of WEP-driven loss of Van Allen belt electrons by combining experimental satellite results, Trimpi observations, and global lightning distributions.

2. WEP Measurements by the Seep Experiment

[6] One of the most comprehensive studies of the dynamics of WEPs burst made use of data from 2–1000 keV particle spectrometers in the Stimulated Emissions of Energetic Particles (SEEP) experiment. A detailed examination has been reported of a SEEP–observed WEP event (“event D”) that occurred at ~03:33 UT, 9 Sept 1982, at L = 2.23 [*Voss et al.*, 1998]. It was found that during the 0.2 s WEP burst 7.4×10^3 electrons cm^{-2} with kinetic energies >45 keV were lost into the atmosphere. Because of the back-scattering of some of the WEP electrons, the overall event was made up of a ~2 s train of bursts, where each burst deposited a decreasing amount of electrons into the atmosphere. We estimate from Figure 15 of *Voss et al.* [1998] that each burst was roughly half the magnitude of that occurring in the conjugate hemisphere, and therefore the total number of electrons lost in this WEP event will have been 14.8×10^3 electrons cm^{-2}.

[7] In order to determine the significance of the WEP-driven losses to the inner-belt, it is necessary to compare this process with the electron fluxes that would normally be present in a flux tube at L = 2.23. We make use of the empirical AE-5 Inner Zone Electron Model [*Teague and Vette*, 1972], which provides analytic functions for the unidirectional differential energy flux based on data collected during solar maximum conditions. For our purposes AE-5 is more useful than the current standard trapped electron model for solar max conditions, AE-8MAX [*Vette*, 1991]. We note, however, that the two models produce omnidirectional integral fluxes which are within ~5% of one another at L = 2–3, well within the suggested error estimates for AE-8 of "about a factor of 2" [*Vette*, 1991, pg 4–2].

[8] It is known that the magnitude of the precipitation energy flux for a WEP event is directly proportional to the trapped flux level in the radiation belts near the edge of the loss cone [*Inan et al.*, 1985]. Using AE-5 along with the SEEP observed event D we have determined the differential electron number flux of our WEP burst as shown in Figure 1a. It is more instructive to consider the WEP driven electron losses shown as a fraction of the number of electrons at a given energy in a magnetic flux tube having unit area perpendicular to the geomagnetic field at the top of the atmosphere. Following the approach described in *Voss et al.* [1998] the percentage loss from the overall flux tube population at a given energy has been calculated for the 100 km altitude level at L = 2.23 for electrons with energy 45–1500 keV (after *Rodger et al.* [2002]), and is shown in Figure 1b. Clearly, a single WEP burst causes an extremely small loss from the overall particle population in a given unit area flux tube.

[9] In order to estimate the WEP-driven lifetime of L=2.23 radiation belt electrons, it is necessary to determine a representative rate at which WEP events will deplete the population of a given unit area flux tube. This is considered in Section 3.

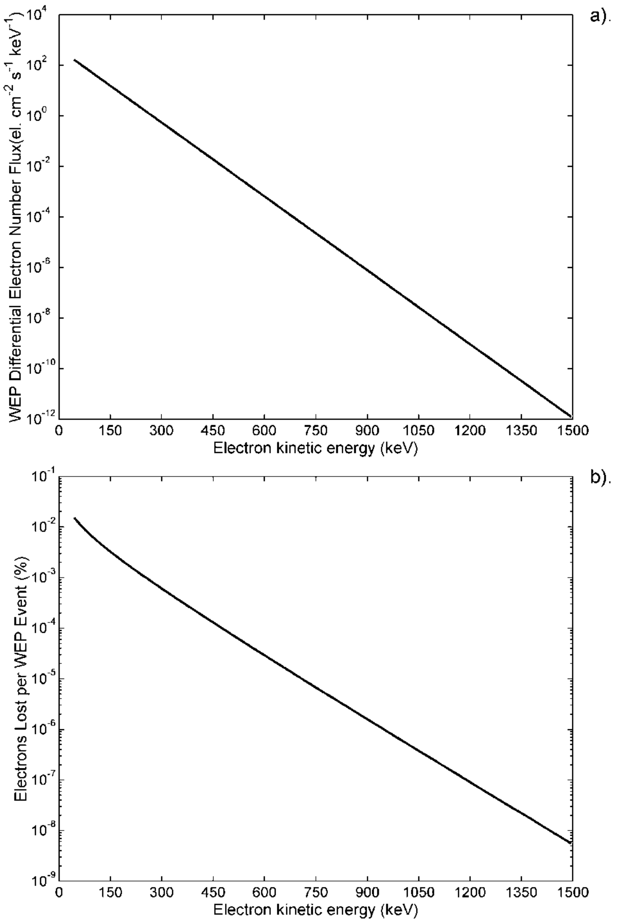

Figure 1. Properties of the 0.2 s WEP burst used in this study, based on the SEEP observed event D and the AE-5 radiation belt model. (a) Differential electron number flux. (b) Loss from a single WEP burst from the overall energetic electron population at L = 2.23.

3. Global Mean WEP Rates

[10] It is well known that the distribution of global lightning activity is complex, with strong dependencies upon season, latitude, and location above land masses rather than oceans [e.g., *Zuelsdorf et al.*, 1997]. However, as the energetic electron lifetime is likely to be considerably longer than the azimuthal drift rates over the kinetic energy range we consider for SEEP event D, the population of any given flux tube will have drifted round the Earth many times over the lifetime. Therefore, we may use a global average WEP rate. Previously authors have examined the observed whistler rate in order to estimate the average WEP rate [e.g., *Burgess and Inan*, 1993]. We will instead make use of observed Trimpi, as it has been suggested that WEP may also be produced by unducted whistlers [*Lauben et al.*, 1999], which are unlikely to observed on the ground in the conjugate hemisphere. A study of Trimpi perturbations observed at Faraday, Antarctica (65.3°S, 64.3°W, L = 2.5) reported that at the typical times of highest Trimpi perturba-

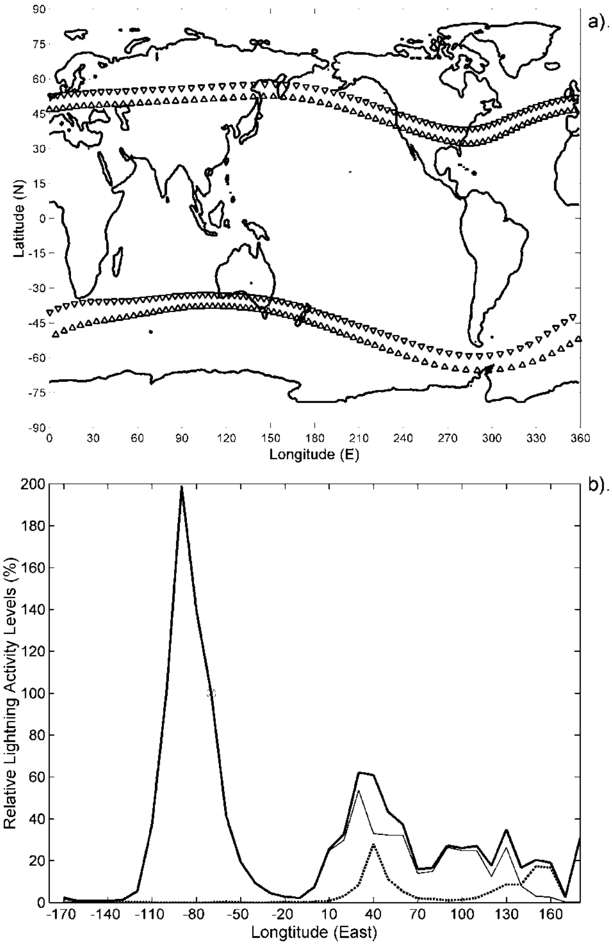

Figure 2. Global lightning distributions used in this study. (a) Location of flux tube footprints for L = 2–2.5 shells at 100 km altitude (triangles). (b) Global lightning activity between L = 2–2.5 relative to the Antarctic Peninsula Trimpi perturbation source region (marked by cross).

tion rates (05:30–06:30 UT) the most likely rate was 1/min observed over 115 days from 1993 and 1994 [*Rodger et al.*, 2002]. It has previously been found that Trimpi perturbations observed in the Antarctic Peninsula are strongly associated with high-current cloud to ground lightning occurring around 34°N, 76°W [*Clilverd et al.*, 2002]. This Trimpi perturbation source region corresponds with flux tubes on L = 2–2.5 shells at the 100 km altitude level. The highest Trimpi rates are observed at ~6 UT at the time of low lightning activity levels in the Trimpi source region, far from the time when there is peak lightning activity in the conjugate region (~21 UT). We believe that the mean WEP rate will be at least 1/min at all times, and that WEP rates will peak at considerably more than 1/min when lightning rates peak at ~21 UT. However, Trimpi observations through much of the day are often masked by ionospheric effects and noise levels, and thus lower rates are observed. Following the approach of *Rodger et al.* [2002] we argue that because of the large size and ionization profile of observed WEP patches [*Clilverd et al.*, 2002], the vast majority of observed Trimpi perturbations will be due to approximately equal WEP fluxes occurring across all of this L-shell range. Under these assumptions, the WEP rate experienced by energetic electrons at L = 2.23 for Antarctic Peninsula longitudes is taken to have the constant value throughout the day of 1/min. This value represents an estimate of the average WEP rate, which will vary strongly over the day.

[11] By making use of satellite observed global lightning distributions [e.g., *Zuelsdorf et al.*, 1997], we have estimated the expected WEP rate for flux tubes on L = 2–2.5 shells at 100 km altitude [*Barraclough*, 1987]. The location of these L-shell footprints is shown in Figure 2a (triangles). WEP rates were found for combined northern and southern hemisphere lightning, relative to the 1/min rate from Antarctic Peninsula longitudes. The global lightning activity between L = 2–2.5 relative to the Antarctic Peninsula Trimpi perturbation source region is shown in Figure 2b. The total activity (heavy line), is shown, along with that for only the northern (light) and southern (dashed) hemispheres. Clearly, lightning in North American is dominant for this mechanism inside these L-shells. Making use of the lightning activity across these L-shells, we find that the mean global activity is ~30% of that seen in Antarctic Peninsula longitudes, and hence that the global mean daily WEP rate L=2.23 is 0.3/min.

4. WEP-Driven Electron Lifetimes

[12] We follow previous authors and define the energetic electron lifetime, τ, as the time in which the flux tube electron population at a given L and energy would drop to 1/e of its original density, assuming that pitch angle diffusion near the bounce loss cone is adequate to maintain the percentage flux loss shown in Figure 1b [e.g., *Burgess and Inan*, 1993]. Other source or loss processes are not included in our estimate for τ. The heavy line in Figure 3 shows the energetic electron lifetime at L = 2.23 making use of the global mean WEP rate determined above. Also shown in Figure 3 is an estimate of the electron lifetime due to Coulomb collisions (dashed line), as applied by *Lyons and Thorne* [1973], and calculated values of τ due to plasmaspheric hiss taken from *Lyons et al.*[1972, Figure 7] (shown as diamonds). For electrons with energies <700 keV WEP depletes the inner radiation belts faster than Coulomb collisions. However at 700 keV both of these loss mechanisms are swamped by the plasmaspheric hiss mechanism. At 350 keV WEP and hiss are equally effective at depleting the inner belt. Below 350 keV WEP is the most significant loss process with τ typically about 10 days. This would lead to lower lifetimes for 100 keV electrons at L = 2.25 than calculated by *Abel and Thorne* [1998]. This should be experimentally testable. Although the low energy lifetimes shown in Figure 3 are short, they are still 10 more times larger than the drift periods, as assumed in section 3 (not shown).

5. Discussion and Summary

[13] The variation of WEP-driven τ against electron energy is strongly determined by the spectra of the WEP event relative to the trapped electron spectra, the magnitude of the precipitated electrons, as well as the global WEP rate. In the calculations presented in this paper, we have made use of empirical, or directly experimental, measurements to

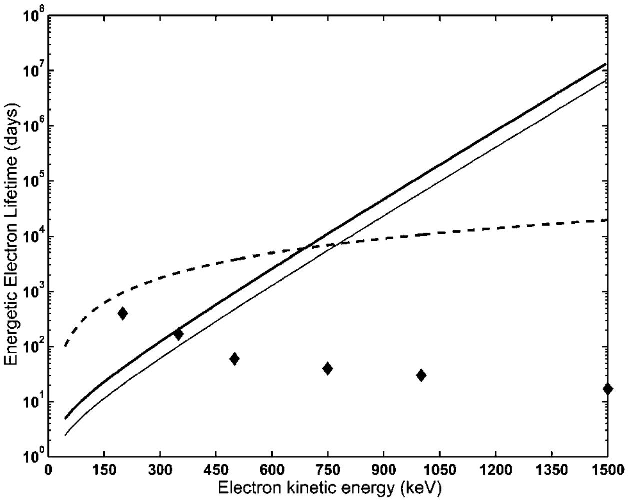

Figure 3. Lifetime of energetic electrons in flux tubes at L = 2.23 due to global mean WEP rates of 0.25/min (heavy line) and 0.5/min (light line). The dashed line shows the estimated lifetime due to Coulomb scattering driven losses, while the diamonds indicate the lifetime due to plasmaspheric hiss losses.

quantify these parameters. There is, however, significant uncertainty in all of these factors. One example is the choice of trapped electron spectra, taken above from AE-5. Another experimentally based choice would be to use SEEP observations of the trapped energetic particle distribution near the edge of the loss cone [*Inan et al.*, 1989]. This leads to short lifetimes (<10 days) for radiation belt electrons with kinetic energies <300 keV, but also indicates similarly short lifetimes for energetic electrons >700 keV (not shown). In an attempt to gain an experimental comparison between the two trapped spectra, we have examined the modification produced by such WEP bursts in the ionospheric D-region, following on from *Rodger et al.* [2002]. However, the differences between the calculated ionospheric modifications are not so large as to be able to determine if one is more realistic than the other (not shown). At this stage we favor the use of the AE-5 trapped spectra, as this involves the direct comparison of like with like. At this stage direct measurement of in-situ WEP losses are extremely rare, leaving us unable to determine the typical range of WEP magnitudes.

[14] It should be noted that as WEP driven radiation belt losses are driven by high-current cloud-to-ground lightning, there will significant variation in the importance of WEP losses. The global mean WEP rate for flux tubes on L = 2–2.5 shells at 100 km altitude is strongly influenced by the Antarctic Peninsula Trimpi source sector. While the mean Trimpi perturbation rate observed in the Antarctic Peninsula is normally ~1/min, it was twice this value for 30% of the days examined, producing lifetimes as shown by the light line in Figure 3. Although it appears that WEP-driven losses are on average less significant than plasmaspheric hiss, there are likely to be periods where global WEP rates are much higher, and that WEP-driven losses may be dominant over plasmaspheric hiss for short time periods. A global WEP rate of 2.3/min, corresponding to the peak Antarctic Peninsula observed rate of 7/min [*Rodger et al.*, 2002], would cause WEP driven losses to be as effective as plasmaspheric hiss for electron energies of ~450 keV and more effective for lower energies.

[15] Our modeling suggests that long-term WEP driven losses are more significant than all other inner radiation belt loss processes for electron kinetic energies in the range 40–350 keV. We therefore anticipate a faster depletion rate and thus lower lifetimes than previously calculated. For energetic electrons with kinetic energies greater than >350 keV, the near constant losses from plasmaspheric hiss dominates over WEP losses, which are of comparatively higher magnitude but with low occurrence rates.

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M. A. Clilverd, Physical Sciences Division, British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, England, U.K. (M.Clilverd@bas.ac.uk)
C. J. Rodger, Department of Physics, University of Otago, P.O. Box 56, Dunedin, New Zealand. (crodger@physics.otago.ac.nz)