Model of the energization of outer-zone electrons by whistler-mode chorus during the October 9, 1990 geomagnetic storm

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[1] Relativistic (>1 MeV) 'killer electrons' are frequently generated in the Earth's inner magnetosphere during the recovery phase of a typical magnetic storm. We test the hypothesis that the energization of electrons takes place by means of stochastic gyroresonant interaction between lower-energy (several 100 keV) seed electrons and whistler-mode chorus waves. We develop a model kinetic equation for the electron energy distribution, and utilize both electron and whistler-mode wave data at $L = 4$ for a typical geomagnetic storm (on October 9, 1990) from instruments carried on the Combined Release and Radiation Effects Satellite (CRRES). Our model solutions are found to match well with the CRRES profiles of the electron flux. We conclude that the mechanism of stochastic acceleration by whistler-mode turbulence is a viable candidate for generating killer electrons, not only for the storm considered, but for similar storms with a several-day recovery phase containing prolonged substorm activity. *INDEX TERMS:* 2720 Magnetospheric Physics: Energetic particles, trapped; 2730 Magnetospheric Physics: Magnetosphere—inner; 2772 Magnetospheric Physics: Plasma waves and instabilities; 2788 Magnetospheric Physics: Storms and substorms. **Citation:** Summers, D., C. Ma, N. P. Meredith, R. B. Horne, R. M. Thorne, D. Heynderickx, and R. R. Anderson, Model of the energization of outer-zone electrons by whistler-mode chorus during the October 9, 1990 geomagnetic storm, *Geophys. Res. Lett.*, *29*(24), 2174, doi:10.1029/2002GL016039, 2002.

1. Introduction

[2] Highly energetic relativistic (>1 MeV) electrons are often generated in the outer radiation zone ($3 < L < 7$) of the Earth's magnetosphere one or two days after the initiation of a magnetic storm ($L = R/R_E$, with R the radial distance in the equatorial plane, and R_E the Earth's radius), e.g., *Baker et al.* [1997], *Li et al.* [1997], and *Reeves et al.* [1998]. These relativistic electrons have been colloquially called 'killer electrons' because they present a serious potential hazard to orbiting spacecraft, space stations, and humans in space, e.g., *Horne* [2002a]. During the main phase of a typical storm, when there are large negative values of the interplanetary magnetic field and large sudden increases in solar wind density and pressure, the relativistic electron flux in the outer zone ($3 \leq L \leq 7$) can decrease by two or three orders of magnitude over a few hours. Then, during the recovery phase, fluxes can increase to values in excess of pre-storm levels by a factor of 10 to 10^3, the peak being reached several days after the initiation of the storm.

[3] There is no widely accepted explanation, as yet, for the stormtime generation of the relativistic electrons. Necessary ingredients for the stormtime generation of relativistic (>0.5 MeV) outer-zone electrons appear to be (a) a sufficiently strong southward component of the interplanetary magnetic field, (b) a sufficiently high (>500 km s^{-1}) solar wind speed, and (c) an abundant supply of substorm-produced seed electrons of energies $\sim$100–300 keV which are subsequently accelerated during the storm recovery phase. Although various physical mechanisms have been proposed for generating relativistic electrons during storms (e.g., *Friedel et al.* [2002]), either the mechanisms have deficiencies, or remain to be well tested against observations. Wave-particle interactions play a fundamental role in electron acceleration and loss processes during magnetic storms, e.g., *Horne* [2002b]. In the present study, we test a specific mechanism, that of gyroresonant acceleration by whistler-mode chorus waves, as a generator of relativistic electrons, and we utilize both electron flux and whistler-mode wave data for a particular storm. While this acceleration mechanism has been discussed in other studies [*Temerin et al.*, 1994; *Summers et al.*, 1998, 2001; *Horne and Thorne*, 1998; *Ma and Summers*, 1998; *Roth et al.*, 1999; *Summers and Ma*, 2000], it has not been evaluated hitherto by using simultaneous stormtime observations of electrons and waves. We formulate a model kinetic equation for the electron energy distribution, and utilize data from the Combined Release and Radiation Effects Satellite (CRRES). Electron data used in the present study were collected by the Medium Electrons A (MEA) experiment [*Vampola et al.*, 1992] and the wave data by the University of Iowa plasma wave experiment [*Anderson et al.*, 1992].

2. Observations

[4] *Meredith et al.* [2002a] analyzed wave and particle data from CRRES for three event studies, and provided evidence for an association between enhanced whistler-mode chorus activity and the acceleration of electrons to relativistic energies. One of these events, the October 9,

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1990 storm, is selected here for a quantitative analysis of electron stochastic acceleration. This is a good example of a strong storm with associated prolonged substorm activity during the main and recovery phases. Figure 1 shows the time variation of *D*st for the selected storm, with a minimum *D*st of −133 nT occurring at 08.30 UT on October 10, 1990. The main phase starts at 00.30 UT on October 10, and lasts for approximately 8 hours. A relatively long recovery phase of approximately 3.25 days then follows, with the *D*st index eventually returning to quiet pre-storm values at 14.30 UT on October 13. During the recovery phase, data were selected from the outbound and inbound spacecraft orbits 187, 189, 190, and 192, each at the location $L = 4.0$. Also shown in Figure 1 are time profiles of the magnetic activity index K_p (color-coded) and the auroral activity *AE* index (as a line plot). The periods of elevated values of K_p (>5) and *AE* (>300) show that the storm is accompanied by significant substorm activity. Whistler-mode chorus waves are enhanced near the equatorial ($|\lambda_m| < 15°$) region in a broad frequency band ($0.1-0.5 f_{ce}$), f_{ce} being the electron gyrofrequency (Figure 1, top). Enhanced chorus activity has been shown to be generally associated with enhanced substorm activity [*Meredith et al.*, 2001]. At the specific location $L = 4$, there are 8 point-measurements for the waves and electrons during the storm recovery period, corresponding to the outbound and inbound passes of orbits 187, 189, 190, and 192. The value $L = 4$ was chosen because physical processes not specifically included in this investigation, in particular that of radial diffusion, are expected to be insignificant in the electron acceleration process at this location [*Brautigam and Albert*, 2000; *Meredith et al.*, 2002b]. Our choice of orbits is such that the observations at $L = 4$ all lie within ±15° of the equator. This reduces modulation in the flux caused by changing magnetic latitude, and also means that we use equatorial lower-band chorus data.

[5] In Figure 1, color-coded spectral wave intensities are plotted in $nT^2\ Hz^{-1}$ as a function of relative frequency (f/f_{ce}), at $L = 4$. By comparing the pre-storm intensity profile (for orbit 182) with the recovery phase profiles, it is evident that major enhancements in intensity occur throughout the recovery phase as a result of elevated substorm activity. The average wave amplitude, corresponding to an average intensity profile calculated from the 8 outbound and inbound profiles for orbits 187, 189, 190 and 192, is 24.7 pT over the frequency range $0.1 < f/f_{ce} < 0.5$, compared to a quiet-time typical amplitude of less than 1 pT.

[6] The corresponding temporal response of the electron perpendicular flux at $L = 4$ is shown in Figure 2. Plots of the flux ($cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}$) as a function of *E*, the electron kinetic energy in units of rest energy, are given for the outbound passes of the orbits 187, 189, 190, and 192 occurring during the primary recovery phase, as well as for the orbits 194 and 204. Outbound orbit 186 at $L = 4$ marks the time of *D*st minimum, and occurs prior to the injection of lower energy (hundreds of keV) seed electrons. Orbit 194 marks the end of the primary recovery phase of the storm at which *D*st ≈ 0, and the period between orbits 194 and 204 can be regarded as an extended recovery phase, with the entire relativistic electron event terminating at orbit 204. During the main phase of the storm, which takes place prior to the outbound leg of orbit 186, there is a sharp electron flux drop-out at all energies [*Meredith et al.*, 2002a]. The fluxes then start to recover as the *D*st index increases, and by the outbound orbit 187 the flux of seed electrons with energies less than 500 keV is enhanced over pre-storm levels. Relativistic (>500 keV) electron fluxes, however, during outbound orbit 187 remain depleted in comparison to pre-storm levels. Throughout the recovery phase, the fluxes of lower energy (<500 keV) electrons remain remarkably constant. In fact, the point $j = j_s = 8 \times 10^3\ cm^{-2}\ sec^{-1}\ sr^{-1}\ keV^{-1}$, $E = E_s = 0.9$ ($E_{kin} = 460$ keV) is essentially a fixed anchor point in the data. The anchor point is due to self-limiting electron trapping for $E < E_s$, as described by *Meredith et al.* [2002b]. The fluxes of higher energy (>500 keV) electrons increase gradually during the recovery phase, simultaneous with the enhancements in chorus wave intensities shown in Figure 1. For 1.5 MeV electrons, fluxes increase from values below pre-storm levels near the beginning of the recovery phase (outbound orbit 187) to more than 10 times pre-storm values by the end of the event (outbound orbit 204). Evidence for resonant wave scattering in the electron pitch-angle distributions has been found by *Horne et al.* [2002] for this event.

3. Model

[7] We further extend the *Summers and Ma* [2000] model of energy diffusion of relativistic electrons resulting from gyroresonant interaction with whistler-mode waves in the magnetosphere. We use quasi-linear diffusion theory to formulate a kinetic (Fokker-Planck) equation describing the evolution in time *t* of the electron energy distribution $\Phi(E, t)$, where $E = E_{kin}/(m_e c^2) = \gamma - 1$ is the particle kinetic energy in units of rest energy, $\gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor, *v* is the particle speed, m_e is the electron rest mass, and *c* the speed of light. The kinetic equation is

$$\frac{\partial}{\partial t}(\Phi(E,t)) = \frac{\partial^2}{\partial E^2}[D(E)\Phi(E,t)] - \frac{\partial}{\partial E}[(A(E) - \dot{\varepsilon})\Phi(E,t)] - \frac{\Phi(E,t)}{T_{loss}}, \quad (1)$$

where $D(E)$ is the energy diffusion coefficient due to gyroresonant interaction of the electrons with the small-amplitude whistler-mode turbulence; $A(E)$ is the systematic acceleration rate; $\dot{\varepsilon}$ is the energy loss rate due to Coulomb collisions and synchrotron radiation [*Summers and Ma*, 2000]; and T_{loss} is the mean effective loss-time of electrons due to pitch-angle scattering by plasma waves and other processes. In deriving the kinetic equation, we have assumed that the electron distribution function is isotropic, and we have performed averaging with respect to pitch angle.

[8] The basic input parameters, derived from data, to be inserted into the kinetic equation are the values of the local magnetic field B_0, the local electron number density n_0, and the wave spectral intensity $\tilde{W}(nT^2\ Hz^{-1})$ defined over a specified frequency range $f_1 < f < f_2$. Using these input quantities, we can then calculate the electron gyrofrequency f_{ce}, the electron plasma frequency f_{pe}, the cold-plasma parameter $\alpha = (f_{ce}/f_{pe})^2$, and the relative wave power $R = W_{TOT}/W_0$, where the total wave intensity is $W_{TOT} = \int_{y_1}^{y_2} \tilde{W} f_{ce} dy$, with $y_1 = f_1/f_{ce}$, $y_2 = f_2/f_{ce}$, and $W_0 = B_0^2/8\pi$ is the background magnetic field energy. In calculating the cyclotron-resonant energy diffusion coefficient *D* and the systematic acceleration rate *A*, we have utilized classical

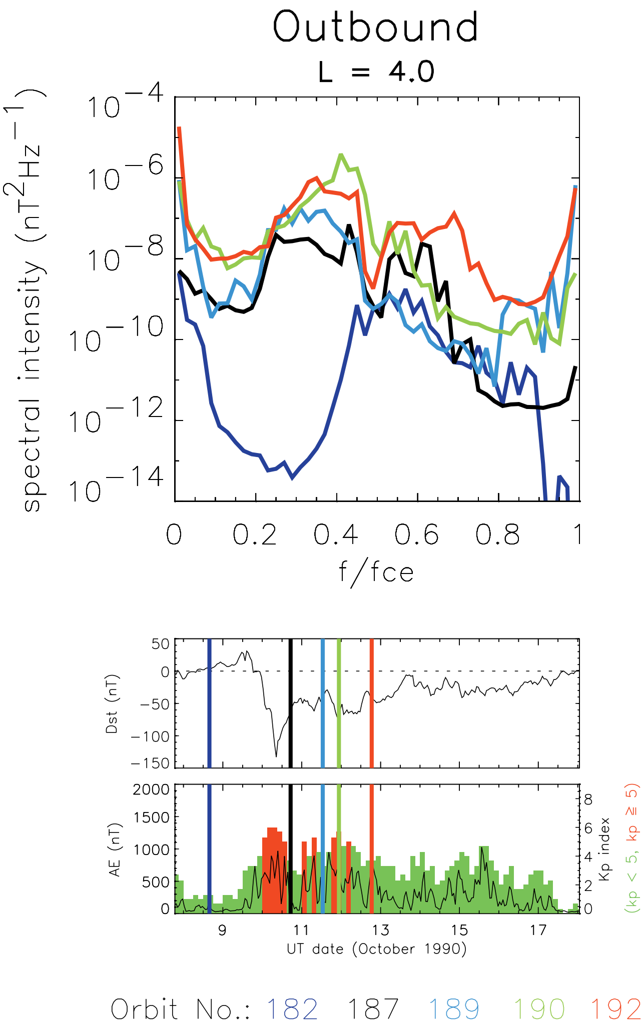

Figure 1. The upper panel shows the spectral intensities of whistler-mode chorus waves measured on CRRES, at $L = 4$, as a function of relative frequency $y = f/f_{ce}$, for the color-coded outbound orbits 182, 187, 189, 190, and 192. The lower panel shows the variation of the *D*st index, the color-coded K_p index, and a line plot of the *AE* index. The vertical stripes mark the color-coded orbits.

quasi-linear theory, and a reduced form of the Doppler resonance condition, thereby avoiding the need for multiple-resonance calculations. Further, we use the whistler dispersion relation for waves propagating parallel to the background magnetic field in a cold plasma. The formulae for D and A comprise integrals over wave frequency involving the wave intensity $\tilde{W}$, and are given as follows:

$$D(E) = D_1 \int_{y_1}^{y_2} X\tilde{W} f_{ce} dy, \quad A(E) = A_1 \int_{y_1}^{y_2} Z\tilde{W} f_{ce} dy, \qquad (2)$$

where

$$X = \left[1 - \frac{\alpha}{E(E+2)}\left(\frac{1-y}{y}\right)\right] Z, \quad Z = y^{1/2}(1-y)^{3/2},$$

$$D_1 = \frac{\pi}{2} f_{ce} R\alpha^{3/2}[E(E+2)]^{1/2}(E+1)^{-1} W_{TOT}^{-1},$$

$$A_1 = \pi f_{ce} R\alpha^{3/2}[E(E+2)]^{-1/2} W_{TOT}^{-1}. \qquad (3)$$

Results (2) are valid for energy $E > [1 + \alpha(1 - y_1)/y_1]^{1/2} - 1$.

[9] The kinetic equation is solved in the region $E \geq E_s$, where the point $\Phi = \Phi(E_s, t) = \Phi_s$, $E = E_s$ is fixed for all time $t \geq 0$, and Φ_s corresponds to the measured electron flux j_s. By choosing (Φ_s, E_s) as a fixed inner point in the model, we implicitly regard the lower-energy ($E < E_s$) electron population as a steady-state source. The storm recovery phase is regarded as beginning with outbound orbit 187, which is taken to correspond to the initial time $t = 0$ in the solution of the kinetic equation. The particle distribution $\Phi(E, 0)$ at $t = 0$ is assumed to be equal to the measured particle flux profile (for $E > E_s$) for outbound orbit 187. The input wave intensity $\tilde{W}$ during the recovery phase is calculated from a simple average of the 8 data profiles of the wave intensities corresponding to the outbound and inbound orbits 187, 189, 190 and 192. Likewise, input values of the local magnetic field B_0 and local electron number density n_0 over the recovery phase are taken to be averages of the measured values at these 8 orbits. The kinetic equation is solved numerically by the Crank-Nicholson implicit differencing method. Model solutions for the particle flux j (converted from the solutions for Φ) are shown in Figure 2 corresponding to the parameter values $B_0 = 442$ nT, $n_0 = 16.6$ cm^{-3}, $f_{ce} = 12.4$ kHz, $f_{pe} = 36.6$ kHz, $\alpha = 0.115$, $y_1 = 0.05$, $y_2 = 0.23$, $R = 3 \times 10^{-9}$, and $T_{loss} = 1.5$ day. Experimental data to determine T_{loss} for this storm were unavailable. The value adopted here for T_{loss} represents a best available estimate, corresponding to 10^{-3} times the rate of strong diffusion pitch-angle scattering for high energy electrons [*Summers and Thorne*, 2002]. The model flux profiles are shown as dashed curves, and correspond to the times $t = 0$, 16 hr, 1, 2, 3, 4, 10 day. The measured flux

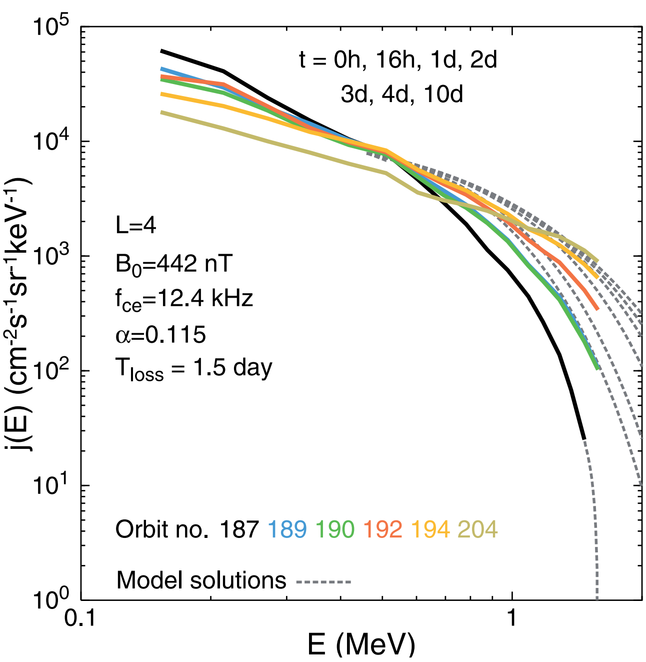

Figure 2. Color-coded perpendicular electron fluxes measured on CRRES, at $L = 4$, as a function of electron kinetic energy E, corresponding to the color-coded outbound orbits 187, 189, 190 and 192 referred to in Figure 1. The model solutions at the indicated times are shown as dashed lines. Additional measured electron flux profiles are given for outbound orbits 194 and 204.

profiles shown in Figure 2 for the outbound orbits 187 (black), 189 (blue), 190 (green), 192 (red), 194 (orange), and 204 (brown) correspond to the respective times $t = 0$, 19.6 hr, 29.5 hr, 49.3 hr, 69 hr, and 7 day. It is evident from Figure 2 that the bulk of the particle acceleration takes place during the ($\approx$3 day) storm recovery phase between orbits 187 to 194, and that the formation of the high-energy tail of the particle flux distribution is reasonably well represented by the model solutions over this period. Our investigation therefore supports the hypothesis that gyroresonant interaction between seed electrons and whistler-mode chorus waves is a primary generator of the killer electrons observed at $L = 4$ during the October 9, 1990 magnetic storm.

4. Summary

[10] The purpose of this study has been to examine quantitatively the effectiveness of chorus-driven stochastic acceleration as a mechanism for producing stormtime relativistic electrons during the October 9, 1990 magnetic storm. We have formulated a model kinetic equation for the electron energy distribution, and have utilized both electron and chorus wave data from CRRES. The model solutions successfully reproduce the observed spectral hardening, thereby providing support for gyroresonance of electrons with whistler-mode chorus as the predominant local acceleration mechanism. Our study is one of the first to make use of simultaneous electron and wave data for a given storm in order to evaluate a proposed mechanism for generating killer electrons. While the present investigation involves the particular October 9, 1990 storm, our results should be of more general application. Specifically, we expect the mechanism of stochastic acceleration by whistler-mode turbulence to be a strong candidate for generating relativistic 'killer' electrons in the region $3 \leq L \leq 5$ during similar 'typical' magnetic storms, namely those with long-lasting (several day) recovery phases containing prolonged substorm activity.

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