

1 Electron scattering by whistler-mode ELF hiss in 2 plasmaspheric plumes

Danny Summers¹, Binbin Ni¹, Nigel P. Meredith², Richard B. Horne²,
Richard M. Thorne³, Mark B. Moldwin⁴, and Roger R. Anderson⁵

R. R. Anderson, Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, IA 52242-1479, USA. (e-mail: roger-r-anderson@uiowa.edu)

R. B. Horne, and N. P. Meredith, British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge, CB3 0ET, UK. (email: r.horne@bas.ac.uk; nmer@bas.ac.uk)

M. B. Moldwin, Institute of Geophysics and Planetary Physics and Department of Earth and Space Sciences, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90095-1567, USA. (e-mail: mmoldwin@igpp.ucla.edu)

B. Ni, and D. Summers, Department of Mathematics and Statistics, Memorial University of Newfoundland, St. John's, Newfoundland A1C 5S7, Canada. (e-mail: bbni@math.mun.ca; dsummers@math.mun.ca)

R. M. Thorne, Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90095-1567, USA. (e-mail: rmt@atmos.ucla.edu)

¹Department of Mathematics and

3 **Abstract.** Non-adiabatic loss processes of radiation belt energetic elec-
4 trons include precipitation loss to the atmosphere due to pitch-angle scat-
5 tering by various magnetospheric plasma wave modes. Here we consider elec-
6 tron precipitation loss due to pitch-angle scattering by whistler-mode ELF
7 hiss in plasmaspheric plumes. Using wave observations and inferred plasma
8 densities from the Plasma Wave Experiment on the Combined Release and

Statistics, Memorial University of

Newfoundland, St. John's, Newfoundland,
Canada.

²British Antarctic Survey, Natural
Environment Research Council, Cambridge,
United Kingdom.

³Department of Atmospheric and Oceanic
Sciences, University of California, Los
Angeles, USA.

⁴Institute of Geophysics and Planetary
Physics and Department of Earth and
Space Sciences, University of California, Los
Angeles, USA.

⁵Department of Physics and Astronomy,
University of Iowa, Iowa City, USA.

9 Radiation Effects Satellite (CRRES), we analyze plume intervals for which
10 well determined hiss spectral intensities are available. We then select 14 rep-
11 resentative plumes for detailed study, comprising 10 duskside plumes and 4
12 non-duskside plumes, with local hiss amplitudes ranging from maximum val-
13 ues of above 300 pT to minimum values of less than 1 pT. We estimate the
14 electron loss timescale τ_{loss} due to pitch-angle scattering by hiss in each cho-
15 sen plume as a function of L -shell and electron energy; τ_{loss} is calculated
16 from quasi-linear theory as the inverse of the bounce-averaged diffusion rate
17 evaluated at the equatorial loss cone angle. We find that pitch-angle scat-
18 tering by hiss in plumes can be efficient for inducing precipitation loss of outer-
19 zone electrons with energies throughout the range 100 keV - 1 MeV, though
20 the magnitude of τ_{loss} can be highly dependent on wave power, L -shell, and
21 electron energy. For 100 keV - 200 keV electrons, typically $\tau_{loss} \sim 1$ day while
22 the minimum loss timescale $(\tau_{loss})_{min} \sim$ hours. For 500 keV - 1 MeV elec-
23 trons, typically $(\tau_{loss})_{min} \sim$ days, while $(\tau_{loss})_{min} < 1$ day in the case of
24 large wave amplitude (~ 100 's pT). Apart from inducing direct precipita-
25 tion loss of MeV electrons, scattering by hiss in plumes may reduce the gen-
26 eration of MeV electrons by depleting the lower-energy electron seed pop-
27 ulation. Models of the dynamical variation of the outer-zone electron flux
28 should incorporate electron precipitation loss induced by ELF hiss scatter-
29 ing in plasmaspheric plumes.

1. Introduction

30 In order to understand and quantify energetic electron flux variations in the inner
31 magnetosphere, it is necessary to assess both the electron energization and loss processes.
32 Loss mechanisms may be adiabatic, which are temporary, or non-adiabatic which result in
33 net particle loss. Non-adiabatic loss processes include precipitation loss to the atmosphere
34 due to pitch-angle scattering by plasma waves, and loss due to particle drift across the
35 magnetospheric boundary. Radiation belt electrons can undergo gyroresonant pitch-angle
36 scattering by various wave-modes, including whistler-mode VLF chorus, plasmaspheric
37 ELF hiss, and electromagnetic ion cyclotron (EMIC) waves, e.g., see *Summers et al.*
38 [2007a, 2007b] and references therein. In the present paper we analyze a particular form
39 of electron precipitation loss, namely that due to pitch-angle scattering by ELF hiss in
40 plasmaspheric ‘plumes’.

41 The plasmasphere is a cold (a few eV), dense ($10 - 10^4 \text{ cm}^{-3}$) plasma torus surrounding
42 the Earth in the innermost magnetosphere [e.g., *Carpenter, 1963; Chappell et al., 1970;*
43 *Carpenter and Park, 1973; Horwitz et al., 1990; Carpenter and Lemaire, 1997; Lemaire*
44 *and Gringauz, 1998; Ganguli et al., 2000; Goldstein, 2006; Dent et al., 2006*]. The multi-
45 ion (H^+ , He^+ , O^+) plasma comprising the plasmasphere derives from the ionosphere and
46 co-rotates with the Earth. The region of cold plasma rotation and the overall shape of the
47 plasmasphere is controlled by the interaction of the co-rotational electric field and the solar
48 wind influenced dawn-to-dusk cross-tail electric field. During intense geomagnetic storms
49 the plasmaspheric boundary layer, or plasmopause, can lie inside $L = 2$ for several days
50 [*Baker et al., 2004*], while during prolonged periods of quiet geomagnetic conditions the

51 plasmasphere can extend to beyond geosynchronous orbit ($L \sim 6.6$) and possess no distinct
52 outer boundary [*Goldstein et al.*, 2003]. Following geomagnetically disturbed periods,
53 and as a result of interplay between forces driving the plasma sunward and corotational
54 forces, plasma typically drains from the body of the plasmasphere in the afternoon local
55 time sector. The resulting large-scale plasma structures which stretch toward the outer
56 magnetosphere are usually attached to the plasmasphere and are called plasmaspheric
57 plumes or plasmaspheric drainage plumes. Historically, they have been called tails [*Taylor*
58 *et al.*, 1971] or detached plasma elements (or blobs) [*Chappell*, 1974]. Using plasma density
59 data inferred from the Plasma Wave Experiment on the Combined Release and Radiation
60 Effects Satellite (CRRES), *Moldwin et al.* [2004] found that plumes can exist at all local
61 times under all levels of geomagnetic activity, but that most were observed in the noon-
62 to-dusk sector following enhanced geomagnetic activity. In many of the methods hitherto
63 used it should be noted that whether or not the observed plasma structures were attached
64 to the plasmasphere could not easily be determined. Excellent global images of evolving
65 plasmaspheric plumes have been provided by the extreme ultraviolet (EUV) imager of the
66 Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite [e.g., *Sandel*
67 *et al.*, 2003; *Goldstein et al.*, 2003, 2004, 2005; *Spasojevic et al.*, 2003, 2004; *Burch*, 2006;
68 *Goldstein*, 2006]. *In situ* measurements from the four CLUSTER satellites confirm that
69 plumes rotate around the Earth, with their feet attached to the main plasmasphere fully
70 co-rotating, but with their tips often rotating more slowly and moving outward away from
71 the Earth [*Darrouzet et al.*, 2006].

72 Plasmaspheric hiss is a broadband ELF electromagnetic whistler-mode emission which
73 occurs in the frequency range from ~ 100 Hz to several kHz. Hiss is present over a

74 broad region of the plasmasphere even during geomagnetically quiet periods and intensifies
75 during storms or substorms [*Smith et al.*, 1974; *Thorne et al.*, 1974; *Meredith et al.*, 2004].
76 Broadband amplitudes of hiss range from 10 pT or below during quiet periods to ~ 100 's
77 pT during disturbed times [*Smith et al.*, 1974; *Tsurutani et al.*, 1975; *Meredith et al.*,
78 2004]. Hiss is generally field-aligned near the magnetic equator and tends to propagate
79 more obliquely at higher latitudes [*Parrot and Lefevre*, 1986; *Santolik et al.*, 2001]. There
80 are extensive observations of plasmaspheric hiss, e.g., see *Hayakawa and Sazhin* [1992],
81 *Meredith et al.* [2004], *Masson et al.* [2004] and references therein. Whistler-mode hiss
82 has also been observed in plasmaspheric plumes [*Chan and Holzer*, 1976; *Cornilleau-*
83 *Wehrlin et al.*, 1978; *Hayakawa et al.*, 1986; *Parrot and Lefevre*, 1986]. Analyzing
84 CRRES wave and particle data, *Meredith et al.* [2004] found that plasmaspheric hiss peaks
85 in particular equatorial ($|\text{MLAT}| < 15^\circ$) and midlatitude ($15^\circ < |\text{MLAT}| < 30^\circ$) regions,
86 mainly on the dayside, and that generally hiss amplitudes depend on L -shell, MLT and
87 magnetic latitude, as well as substorm activity. Plasmaspheric hiss, together with other
88 whistler-mode emissions [*Abel and Thorne*, 1998], plays an important role in controlling
89 the structure of the Earth's radiation belts. *Lyons and Thorne* [1973] showed that the
90 formation of the quiet-time 'slot' region between the inner ($1.3 < L < 2.5$) and outer
91 ($3 < L < 7$) radiation belts can be explained as an equilibrium balance between inward
92 radial diffusion and pitch-angle scattering loss of energetic electrons to the atmosphere
93 induced by plasmaspheric hiss [*Lyons et al.*, 1972]. Plasmaspheric hiss can also cause
94 scattering loss of MeV electrons from the outer radiation belt over a timescale of days, or
95 less, under appropriate conditions [*Tsurutani et al.*, 1975; *Albert*, 1994, 2003; *Summers*
96 *et al.*, 2007b]. *Meredith et al.* [2006a] used CRRES data to measure the gradual decay

97 of energetic (214 keV - 1.09 MeV) electron fluxes in the outer zone following enhanced
98 geomagnetic activity. *Meredith et al.* [2006a] and *Summers et al.* [2007b] found that
99 scattering by plasmaspheric hiss propagating at zero or small wave normal angles could
100 account for the measured electron decay rates over a wide range of energies and L -shells.

101 The generation mechanism of plasmaspheric hiss has not been fully resolved and remains
102 controversial. There are two leading theories for the source of plasmaspheric hiss, namely,
103 *in situ* natural instability in the magnetosphere [e.g., *Etcheto et al.*, 1973; *Thorne et*
104 *al.*, 1979; *Huang et al.*, 1983], and lightning-generated whistlers [e.g., *Sonwalkar and*
105 *Inan*, 1989; *Draganov et al.*, 1992; *Green et al.*, 2005]. The analysis by *Green et al.*
106 [2005] supporting lightning as the dominant source for plasmaspheric hiss was disputed
107 by *Thorne et al.* [2006]; see also the reply by *Green et al.* [2006]. *Meredith et al.* [2006b]
108 subsequently analyzed the entire CRRES database of plasmaspheric hiss together with
109 the global distribution of lightning and concluded that while higher-frequency hiss (2 -
110 5 kHz) is generated by lightning, lower-frequency hiss (100 Hz - 2 kHz) is generated by
111 natural instability in space. Evidence that lower-frequency hiss intensifies during enhanced
112 geomagnetic activity [e.g., *Meredith et al.*, 2004] points to natural instability as the origin
113 of lower-frequency hiss.

114 There is increasing interest in wave-particle interactions occurring in plasmaspheric
115 plumes with respect to their role in influencing particle dynamics in the inner magne-
116 tosphere. Pitch-angle scattering by EMIC waves in plumes can cause significant precipita-
117 tion loss of energetic protons [*Burch et al.*, 2002; *Spasojevic et al.*, 2004; *Burch*, 2006].
118 *Summers et al.* [2007b] found that an assumed realistic spatial distribution of EMIC waves
119 and hiss in an empirically measured plume could induce rapid scattering loss of outer zone

120 electrons. The relative contributions to electron scattering by hiss and EMIC waves in
121 plumes depend on the electron energy and L -shell, as well as the wave properties; see
122 Figures 21 and 22 of *Summers et al.* [2007b]. In the present paper we analyze hiss-electron
123 interaction in plasmaspheric plumes selected from the CRRES mission. Specifically, we
124 determine intervals during which CRRES crossed a plume and select a subset of plume
125 intervals for which well-observed hiss data are available. We then use quasi-linear theory
126 to determine hiss-induced pitch-angle scattering rates at the loss cone for electrons of
127 specified energy at given L -values. We can thereby estimate timescales for precipitation
128 loss of energetic electrons in the inner magnetosphere due to scattering by hiss in plumes.
129 The present study is the first to determine electron precipitation loss timescales due to
130 scattering by measured hiss in observed plumes. We present our selection of plume in-
131 tervals and associated hiss data in section 2. In section 3 we summarize the necessary
132 quasi-linear theory required for our calculations. In section 4 we present our estimates for
133 electron loss timescales due to scattering by hiss in the chosen plumes. Finally, in section
134 5 we discuss the significance of our results.

2. CRRES plume and wave observations

135 CRRES was launched on 25 July, 1990 and functioned until 12 October, 1991. The
136 spacecraft had a geosynchronous transfer orbit, namely an elliptical orbit with a perigee
137 of $1.05 R_E$ and an apogee of $6.26 R_E$ with respect to the Earth's center, with an inclination
138 of 18.15° . The outermost L -shell reached by CRRES was $L \sim 8$. The orbital period was
139 approximately 9 hours 55 minutes, and the apogee of CRRES precessed from 10.00 MLT
140 to 14.00 MLT through midnight before the mission terminated. The satellite was able to
141 provide excellent coverage of the radiation belts for nearly 15 months since it traversed

142 the inner magnetosphere on average about 5 times per day. The wave data and plasma
143 densities used in this study were obtained from the Plasma Wave Experiment (PWE) on
144 board CRRES. This experiment measured electric fields from 5.6 Hz to 400 kHz, using
145 a 100 m tip-to-tip long wire antenna, with a dynamic range covering a factor of at least
146 10^5 in amplitude [*Anderson et al.*, 1992]. The electric field detector was thus able to
147 detect waves from below the lower hybrid resonance frequency (f_{LHR}) to well above the
148 upper hybrid resonance frequency (f_{UHR}) for a large fraction of each orbit. The maximum
149 plasma density that could be measured was $\sim 2000 \text{ cm}^{-3}$ because of the upper frequency
150 limit of the instrument. The CRRES PWE also included a boom-mounted search coil
151 magnetometer that covered the frequency range from 5.6 Hz to 10 kHz and operated until
152 the March 1991 storm. While the electric field data were sampled with high-frequency
153 resolution by the PWE sweep frequency receiver at eight seconds per spectra above 6.4
154 kHz, the search coil data were sampled by a 14-channel analyzer that sampled the magnetic
155 field eight times per second every other 32 seconds.

156 We determine the presence of a plume by monitoring the behavior of the plasma density
157 as inferred from observations of the upper hybrid resonance frequency. If, while CRRES
158 is clearly outside the plasmasphere, the density suddenly increases, remains high for some
159 time, and then suddenly decreases, we identify the region as a potential plume. We refer
160 to such a region as a plume for simplicity, even though CRRES observations cannot deter-
161 mine if the identified high-density region is attached to the plasmasphere. We also use the
162 absence of electrostatic electron cyclotron harmonic (ECH) waves as a criterion for identi-
163 fying high-density plasma regions, as described by *Meredith et al.* [2004]. Identification of
164 a plume and its boundary can be problematic observationally, and is, to a degree, subjec-

165 tive. Determination of a boundary of a plume is straightforward if it is sharp, and difficult
166 if it is gradual. This situation likewise applies to the determination of the boundary of
167 the plasmopause itself. To complement the techniques applied for identifying plumes in
168 our study, we also make use of the rigorous plume selection criteria of *Moldwin et al.*
169 [2004]. The comprehensive study of plumes during the CRRES mission by *Moldwin et al.*
170 [2004] employed the database of plasmopause locations identified by *Moldwin et al.* [2002]
171 and the empirical plasmaspheric and trough density models developed by *Sheeley et al.*
172 [2001]. These three studies used a common database of plasma density derived from the
173 CRRES Plasma Wave Experiment. *Moldwin et al.* [2002] identified the innermost steep
174 density gradient in the density profile as the plasmopause, a factor of 5 drop within half
175 an L -shell being required. In order to select ‘plasmaspheric’ intervals located outside the
176 plasmopause, *Moldwin et al.* [2004] used $L = 3$ as a dividing line for whether to use the
177 plasmaspheric or trough density model. If the plasmopause is located earthward of $L = 3$,
178 plasmaspheric plume intervals are defined as those whose density exceeds the trough plus
179 one standard deviation density of the *Sheeley et al.* [2001] model. If the plasmopause is
180 located outside of $L = 3$, plasmaspheric plume intervals are defined as those whose density
181 exceeds the *Sheeley et al.* [2001] plasmaspheric model. These models are scaled to each
182 orbit to account for the wide variability in the plasmaspheric density from day to day. The
183 criterion used by *Moldwin et al.* [2004] to select a plume is that the density throughout
184 the requisite interval must exceed the model value of the plasmaspheric density (or trough
185 plus one standard deviation) over a minimum of 8 consecutive observations (a duration
186 of ~ 1 min).

187 In our study we choose 14 plume intervals which we specify in Table 1, according to
188 orbit number, by giving the start and end values of universal time (UT), magnetic local
189 time (MLT), L -shell, and magnetic latitude (MLAT). We have chosen 10 plumes with a
190 duskside MLT location, namely crossed by outbound CRRES orbits 605, 672, 673, 674,
191 810, 869, 871, 939, 941, and 977. The remaining 4 plumes, crossed by outbound orbits
192 302 and 446, and inbound orbits 297 and 446, are non-duskside. The 14 chosen plume
193 crossings are illustrated in Figure 1 in which we also show the approximate trajectory for
194 CRRES orbit 446. Our chosen plumes were likewise identified as plumes by *Moldwin et*
195 *al.* [2004], with the exception of the 3 plumes associated with orbits 297 and 446. These
196 latter plumes were not selected in the *Moldwin et al.* [2004] study because the density
197 did not satisfy their conservative plasmaspheric density criteria. We nevertheless regard
198 these features as representative non-duskside “plumes” because of their distinctly elevated
199 densities compared to the surrounding trough.

200 In some of the selected plumes common to the present study and that of *Moldwin et*
201 *al.* [2004], the specified start and end of the plume interval, as for instance given by
202 L -shell, differ slightly because of the differing plume boundary criteria used in the two
203 studies. This issue does not lead to serious difficulties in our investigation since we base
204 the conclusions of our analysis on electron loss timescales that are calculated ‘well inside’
205 each plume. Thus, possibly spurious ‘edge effects’ are readily eliminated.

206 In Figure 2 we show measured CRRES electron density profiles corresponding to the
207 outbound (blue) and inbound (red) portions of orbits 446, 869, 939, and 977 in the
208 respective panels (a), (b), (c), and (d). For comparison purposes, in each panel we also
209 show upper and lower black curves representing respectively the saturated plasmasphere

density and trough density given by the *Carpenter and Anderson* [1992] model. The
 plume intervals for orbits 446, 869, 939, and 977 as specified by L -shell range in Table 1
 can be observed to match the corresponding intervals of elevated density in panels (a) -
 (d) of Figure 2.

In Figure 3 the measured wave electric field spectral intensities (in $\text{V}^2\text{m}^{-2}\text{Hz}^{-1}$) are
 plotted as a function of UT for the complete CRRES orbits 446, 869, 939, and 977 in the
 respective panels (a), (b), (c), and (d). The magnetic local time, magnetic latitude, and
 L -shell are given at hourly intervals. The solid white line shows the value of the electron
 gyrofrequency f_{ce} , determined from the measured ambient magnetic field, and the dashed
 white lines below f_{ce} represent $0.5f_{ce}$, $0.1f_{ce}$, and the lower hybrid resonance frequency,
 f_{LHR} . The dotted white lines above f_{ce} correspond to the first four harmonics of f_{ce} . The
 solid red line denotes the upper hybrid resonance frequency $f_{UHR} = (f_{pe}^2 + f_{ce}^2)^{1/2}$ (where
 f_{pe} is the electron plasma frequency) calculated from the lower-frequency cut-off of the
 electromagnetic continuum, and the red dashed line represents f_{UHR} calculated from wave
 emissions at f_{UHR} inside the plasmopause. The chosen plumes in the orbits 446, 869, 939,
 and 977 are indicated in Figure 3, together with their associated hiss emissions. Profiles
 of the AE index are provided at one-minute time resolution. The empirical position of
 the plasmopause as defined by *Carpenter and Anderson* [1992] is also marked.

We base the calculations in our study on hiss in the frequency range $104 < f < 1040$
 Hz. The general criterion used in this paper to identify hiss in plumes is that used by
Meredith et al. [2004] to identify plasmaspheric hiss, namely, ECH wave amplitudes for
 frequencies in the range $f_{ce} < f < 2f_{ce}$ must be less than 0.0005 mVm^{-1} in order for
 wave emissions below f_{ce} in the frequency band $104 < f < 1040$ Hz to be identified

233 as hiss. Whistler-mode chorus has a frequency range $0.3 < f < 30$ kHz in the region
 234 $3 < L < 7$. Consequently, chorus can lie in our chosen hiss frequency band at higher
 235 L -shells. However, whistler-mode chorus is usually observed outside the plasmasphere
 236 and high-density regions so can be excluded from consideration in our chosen plumes.
 237 At lower L -shells, magnetosonic waves can also fall into our chosen hiss frequency band.
 238 These waves, which are closely confined to the equatorial region, are enhanced during
 239 active conditions below the lower hybrid resonance frequency f_{LHR} , represented by the
 240 lowest dashed line in the spectrograms in Figure 3. We find no evidence of enhanced
 241 magnetosonic waves within our chosen plumes, except possibly during orbit 871. For the
 242 chosen plume in this orbit, hiss intensities may be slightly over-estimated in the region
 243 $4.25 < L < 5.25$ as a result of contamination by magnetosonic waves.

244 In order to convert observed hiss electric field spectral intensities to magnetic field
 245 intensities, we use a cold-plasma dispersion relation for parallel-propagating whistler-
 246 mode waves (equation (4) of section 3, with $\varepsilon = 0$), Maxwell's induction equation, and
 247 expression (1) given by *Meredith et al.* [2004]. Magnetic field wave intensities over the
 248 frequency range $104 < f < 1040$ Hz are then defined as an integral of the averaged wave
 249 spectral intensity ($\text{nT}^2\text{Hz}^{-1}$). The corresponding wave amplitudes are obtained by taking
 250 the square root of the wave intensities, as detailed in section 3. Conversion from electric
 251 to magnetic fields is relatively insensitive to wave normal angle for wave normal angles
 252 less than 50° , if $f < 0.5f_{ce}$ [*Meredith et al.*, 2004]. We discuss our assumption of parallel
 253 wave propagation further below.

254 In Figure 4 we present hiss spectral intensities in $\text{nT}^2\text{Hz}^{-1}$ within four chosen plumes
 255 during orbits 446, 869, 939, and 977, in the respective panels (a), (b), (c), and (d). In

each panel the spectral intensity is shown at a range of specified L -shells within the
 plume. In Figure 5 we show the measured values of the local hiss amplitudes at the given
 L -shells within each of our 14 chosen plume intervals. Local wave amplitudes range from
 maximum values that exceed 300 pT, for the plumes in orbits 810 and 939, to minimum
 values of less than 1 pT, in orbits 297, 446(In), and 810. This probably represents the
 widest range of hiss amplitudes to be expected in plasmaspheric plumes. Further, since
 we have mainly chosen more-commonly occurring duskside plumes while also including a
 selection of non-duskside plumes, we can consider that the choice of plume intervals for
 our study is reasonably general. For each of the 14 chosen plumes, we present in Table 2
 an average value for the hiss amplitude $\overline{\Delta B}$ (pT) calculated by averaging the measured
 spectral intensity along each plume crossing.

3. Theory

From *Summers* [2005] (equations (10) and (17)), we can write the local pitch-angle diffu-
 sion coefficient for electron cyclotron resonance with field-aligned R-mode electromagnetic
 waves in the form,

$$D_{\alpha\alpha} = \frac{\pi}{2} \frac{|\Omega_e|^2}{B_0^2} \frac{1}{(E+1)^2} \sum_{j=1}^N \left(1 - \frac{\omega_j \cos \alpha}{v k_j}\right)^2 \frac{I(k)}{|v \cos \alpha - d\omega_j/dk_j|} \quad (1)$$

for broadband waves of intensity $I(k)$ or $\hat{I}(f)$ (nT²/Hz), defined on the frequency range
 $\omega_1 < \omega < \omega_2$, where

$$\Delta B^2 = \int_{-\infty}^{\infty} I(k) dk = \int_{f_1}^{f_2} \hat{I}(f) df, \quad (2)$$

and ΔB is the wave amplitude; $f = \omega/2\pi$, $f_1 = \omega_1/2\pi$, and $f_2 = \omega_2/2\pi$; α is the particle
 pitch-angle and v is the particle speed; E is the dimensionless particle kinetic energy
 given by $E = E_k/(m_e c^2) = \gamma - 1$ where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor (c is

the speed of light), and m_e is the electron rest mass; $|\Omega_e| = eB_0/(m_e c)$ is the electron
gyrofrequency, where e is the unit charge and B_0 is the magnitude of the uniform static
magnetic field; the wave frequency ω_j and wavenumber k_j (where $j = 1, 2, \dots, N$) satisfy
the gyroresonance condition

$$\omega_j - v k_j \cos \alpha = |\Omega_e|/\gamma, \quad (3)$$

as well as the dispersion relation,

$$\left(\frac{ck}{\omega}\right)^2 = 1 - \frac{(1 + \varepsilon)/\alpha^*}{(\omega/|\Omega_e| - 1)(\omega/|\Omega_e| + \varepsilon)}, \quad (4)$$

where

$$\alpha^* = \Omega_e^2/\omega_{pe}^2 \quad (5)$$

is an important cold-plasma parameter; $\varepsilon = m_e/m_p$ where m_p is the proton rest mass; and
 $\omega_{pe} = (4\pi N_0 e^2/m_e)^{1/2}$ is the plasma frequency where N_0 is the electron number density.

It is convenient to express formula (1) in terms of the practical wave intensity $\hat{I}(f)$
(nT²/Hz). Then, also introducing the variables,

$$x = \omega_j/|\Omega_e|, \quad y = ck_j/|\Omega_e|, \quad (6)$$

we thereby obtain the result,

$$D_{\alpha\alpha} = \frac{1}{4} \frac{|\Omega_e|^2}{B_0^2} \frac{1}{(E + 1)^2} \sum_{j=1}^N \left(1 - \frac{x \cos \alpha}{y \beta}\right)^2 \frac{\hat{I}(f) |F(x, y)|}{|\beta \cos \alpha - F(x, y)|}, \quad (7)$$

where (from (3))

$$y = (x - 1/\gamma)/(\beta \cos \alpha). \quad (8)$$

In (7), the function $F(x, y)$ is given by expression (C1) in *Summers* [2005]; $\beta = v/c =$
 $[E(E + 2)]^{1/2}/(E + 1)$; and x satisfies the quartic equation (A1) given also in *Summers*

298 In order to apply (7) to the assumed dipole magnetic field of the inner magnetosphere,
 299 it remains to carry out bounce-averaging of (7) to take account of the magnetic mirror-like
 300 geometry. Using the formalism given by *Summers et al.* [2007a], we write the bounce-
 301 averaged diffusion coefficient $\langle D_{\alpha\alpha} \rangle$ as

$$302 \langle D_{\alpha\alpha} \rangle = \frac{1}{S(\alpha_{eq})} \int_0^{\lambda_m} D_{\alpha\alpha}(\alpha) \frac{\cos \alpha \cos^7 \lambda}{\cos^2 \alpha_{eq}} d\lambda, \quad (9)$$

304 where

$$305 S(\alpha_{eq}) = 1.3 - 0.56 \sin \alpha_{eq}. \quad (10)$$

306 In (9), α_{eq} is the equatorial pitch-angle of a particle, and λ is the magnetic latitude of
 307 a particle with pitch-angle α at any point along a field line; α_{eq} , λ , and α satisfy the
 308 relation,

$$309 \sin^2 \alpha = f(\lambda) \sin^2 \alpha_{eq}, \quad (11)$$

310 where

$$311 f(\lambda) = (1 + 3 \sin^2 \lambda)^{1/2} / \cos^6 \lambda. \quad (12)$$

312 λ_m is the latitude of the mirror point of the particle and is given by the equation,

$$313 X^6 + (3 \sin^4 \alpha_{eq}) X - 4 \sin^4 \alpha_{eq} = 0, \quad (13)$$

314 with $X = \cos^2 \lambda_m$.

315 We substitute the local diffusion coefficient $D_{\alpha\alpha}(\alpha)$ given by (7) into (9), and regard α as
 316 a function of α_{eq} and λ , as given by (11). Thus, the bounce-averaged diffusion coefficient
 317 $\langle D_{\alpha\alpha} \rangle$ is a function of α_{eq} . The background magnetic field B_0 occurring in $D_{\alpha\alpha}(\alpha)$ in (9)

318 is replaced by the value,

$$319 \quad B_0 = B_{eq} f(\lambda), \quad (14)$$

320 where

$$321 \quad B_{eq} = B_{local}/f(\lambda_{local}). \quad (15)$$

322 B_{eq} is the equatorial magnetic field, and B_{local} is the locally observed magnetic field at the
 323 observed magnetic latitude λ_{local} , corresponding to the observed L -value. In the absence
 324 of other data to show latitudinal variations in density, we assume that the background
 325 electron number density N_0 is constant along a field line ($N_0 = N_{eq} = N_{local}$). We likewise
 326 assume that the hiss spectral intensity is constant along a field line. From a statistical
 327 survey of CRRES data *Meredith et al.* [2004] found that hiss peaks near the equatorial
 328 ($|\text{MLAT}| < 15^\circ$) and midlatitude ($15^\circ < |\text{MLAT}| < 30^\circ$) regions. CRRES data are not
 329 available at high latitudes ($|\text{MLAT}| > 30^\circ$). Our assumption that hiss is also present at
 330 high latitudes is partially justified by other studies. For example, *Thorne et al.* [1973],
 331 using OGO5 search coil magnetometer data, found that hiss was present on almost every
 332 pass through the plasmasphere. *Thorne et al.* [1973] found little distinction between
 333 lower latitude ($|\text{MLAT}| < 30^\circ$) and high latitude ($|\text{MLAT}| > 30^\circ$) plasmaspheric hiss
 334 emissions, and concluded that properties of hiss remain largely constant throughout the
 335 plasmasphere. We make the assumption that hiss has constant spectral intensity along a
 336 field line on the basis of the best information available. Nevertheless, we recognize that if
 337 the wave power is confined to a lower range of latitudes then our calculations may over-
 338 estimate the higher-energy loss rates since the waves resonate with higher-energy electrons
 339 at higher latitudes. Dependence of electron loss timescales on the latitudinal distribution

of hiss, for a given energy and L -value, is examined by *Summers et al.* [2007b] (section 3).

Evaluation of the integral in (9) can be carried out by standard numerical quadrature which requires evaluation of the integrand at a set of λ -values (quadrature points) in the range $0 < \lambda < \lambda_m$. This requires, in particular, determination of the local diffusion coefficient $D_{\alpha\alpha}(\alpha)$ at the quadrature points. Therefore, at each quadrature point the relevant resonant roots x of the above-noted quartic equation must be found.

We take as an estimate of the electron loss timescale,

$$\tau_{loss} = (1/\delta)(1/\langle D_{\alpha\alpha}^{LC} \rangle), \quad (16)$$

where $\langle D_{\alpha\alpha}^{LC} \rangle$ is the bounce-averaged diffusion coefficient (9) evaluated at $\alpha_{eq} = (\alpha_{LC})_{eq}$ where $(\alpha_{LC})_{eq}$ is the equatorial loss cone angle given by

$$\sin(\alpha_{LC})_{eq} = [L^5(4L - 3)]^{-1/4}. \quad (17)$$

In order to account for the limited angular (MLT) spread of the observed hiss in a given plume, we have inserted into (16) a drift-averaging factor δ which we specify in the following section. The value of τ_{loss} depends on the kinetic energy E , L -shell, the measured hiss spectral intensity \hat{I} , the drift-averaging factor δ , and the equatorial value of the parameter α^* , namely $\alpha_{eq}^* = (\Omega_e^2/\omega_{pe}^2)_{eq}$. The local electron gyrofrequency $|\Omega_e|$ was determined from the CRRES fluxgate magnetometer instrument [*Singer et al.*, 1992]. The local electron plasma frequency ω_{pe} was estimated from CRRES data on electrostatic waves at the upper hybrid frequency and the low-frequency cut-off of electromagnetic continuum radiation, as described by *Meredith et al.* [2002]. In the upper panel of Figure 6 we show the variation of α_{eq}^* with L -value, for the chosen plume intervals, deduced from local CRRES values

362 for $|\Omega_e|$ and ω_{pe} . In the lower panel of Figure 6 we show minimum electron energies for
363 cyclotron resonance with hiss at the frequency 1040 Hz, as a function of L -value, corre-
364 sponding to the upper panel. The minimum resonant energy for electron resonance with
365 hiss is obtained by setting $\sigma = e$ (for electrons) and $s = 1$ (for R-mode waves) in formula
366 (16) of *Summers et al.* [2007a].

367 As described in this section, the determination of the electron loss timescale τ_{loss} in
368 our study assumes that the observed whistler-mode hiss is strictly field-aligned. CRRES
369 data do not provide information on the wave-normal angle or angular spread of the waves.
370 While the assumption that the waves are field-aligned is likely to be an approximation,
371 we consider that our method for calculating τ_{loss} yields reasonably reliable results based
372 on the relatively limited available data. In support of our method, we cite the recent
373 analysis by *Summers et al.* [2007b] who calculated electron loss timescales due to scat-
374 tering by plasmaspheric hiss during low geomagnetic activity in the region $3 < L < 5$.
375 *Summers et al.* [2007b] assumed field-aligned hiss with zero wave-normal distribution and
376 predicted electron loss timescales in good agreement with the measured values obtained
377 from CRRES Medium Electrons A data by *Meredith et al.* [2006a]. It should never-
378 theless be pointed out that inclusion of higher-order scattering could significantly alter
379 the scattering rates near the edge of the loss cone if the hiss becomes strongly oblique.
380 Specifically, we would expect increased loss timescales if the wave-normal angle is large,
381 as demonstrated by *Meredith et al.* [2006a].

4. Electron loss timescales

382 Electron loss timescales calculated in this paper must of course be considered in the
383 context of plume lifetimes overall. Plumets have been observed over the duration of many

384 consecutive CRRES orbits, e.g., see Figure 8 of *Moldwin et al.* [2004]. Since the CRRES
 385 orbital period is about 10 hours, this indicates that plumes can last from 10 hours to more
 386 than 1 day. Global imaging by the EUV imager of the IMAGE satellite has tracked the
 387 evolution of various plumes over several hours to more than 1 day [e.g., *Spasojevic et al.*,
 388 2003; *Goldstein et al.*, 2004]. Very few studies have measured the full global evolution of a
 389 plasmaspheric plume from its creation to its complete dissipation. It is possible that some
 390 plumes persist for several days. For practical purposes, we take an upper limit for the
 391 lifetime of a plume to be 5 days, in which case a value of τ_{loss} exceeding 5 days indicates
 392 that electron scattering by hiss is ineffective for that particular plume at the L -shell and
 393 electron energy under consideration. Plume formations exceeding 5 days in duration are
 394 likely to consist of multiple plumes formed in succession. However, at geosynchronous
 395 orbit ($L \sim 6.6$) cold dense regions in narrow MLT channels are commonly observed over
 396 10-day intervals or longer. In an investigation using multiple geosynchronous satellites,
 397 *Moldwin et al.* [1994] found that plasmaspheric plasma was absent on only 13% of the
 398 days in the study interval.

399 For electrons of a given energy E , we determine the loss timescale τ_{loss} due to scattering
 400 by hiss at a given L -shell in a chosen plume as the inverse of the bounce-averaged diffusion
 401 coefficient $\langle D_{\alpha\alpha} \rangle$ evaluated at the equatorial loss cone angle (formulae (16) - (17)). An
 402 orbiting energetic electron traverses a plume only for a fraction of its orbit. To take
 403 account of the azimuthal (MLT) spread of a plume we have included a drift-averaging
 404 factor δ in (16). The azimuthal spread of a particular plume varies during its evolution
 405 and is typically $0.1 R_E$ to $1.5 R_E$ or more [e.g., *Spasojevic et al.*, 2003; *Darrouzet et*

406 *al.*, 2006]. Hereinafter, we take the drift-averaging factor δ as 6% since this appears to
407 correspond approximately to the ‘typical’ observed azimuthal width of a plume.

408 *Shprits et al.* [2006a] recently analyzed the controlling effect of the pitch-angle scattering
409 rates near the loss cone on energetic electron lifetimes, and found that the electron phase
410 space density reaches an equilibrium shape within hours of the simulation when scattering
411 rates do not drop below 1/10 of the value near the edge of the loss cone for up to a 30°-wide
412 range of pitch angles. In this case, electron lifetimes were found to be primarily controlled
413 by scattering rates near the edge of the loss cone. Further, *Shprits et al.* [2006a] found
414 that while a drop in the diffusion coefficients by a factor of 100 to 1000 near $\alpha_{eq} = 90^\circ$
415 results in weak scattering at high pitch angles, the lower pitch-angle particle distribution
416 decays on a timescale comparable to that determined by the diffusion rate near the edge
417 of the loss cone. Herein, we utilize the findings of *Shprits et al.* [2006a] and estimate
418 electron loss timescales by using the scattering rate at the edge of the loss cone only in
419 those cases in which the diffusion rate is small over a high pitch-angle range narrower than
420 $75^\circ < \alpha_{eq} < 90^\circ$. By using this criterion, we expect that our reported timescales afford
421 reasonable estimates of the decay times of at least the bulk of the electron distribution.

422 In order to carry out accurate drift-averaging of the diffusion rates we require specifi-
423 cation of the complete MLT distribution of hiss spectral intensity. However, only point
424 measurements of the hiss intensity are made by CRRES at particular MLT-values and spe-
425 cific L -shells as the satellite traverses each particular plume. We assume that the average
426 wave power determined along the satellite track is a measure of the MLT wave distribution
427 at a given L -value. Specifically, for each plume we average over all the measured profiles
428 of the hiss spectral intensity, and we use this average intensity, together with the drift-

429 averaging factor δ , to determine the MLT-averaged scattering rate at each L -shell. In
 430 Figure 7 we show examples of profiles of the bounce-averaged and drift-averaged electron
 431 diffusion coefficient $\langle D_{\alpha\alpha} \rangle$ for the plume interval in orbit 977 for electrons of energies 100
 432 keV, 200 keV, 500 keV, and 1 MeV, at the given L -shells. In Figure 8 we plot the electron
 433 loss timescale τ_{loss} at the specified energies as a function of L -shell for the chosen plumes
 434 in orbits 446 (Out), 869, 939, and 977 in the respective panels (a), (b), (c), and (d). Hiss
 435 intensity for orbit 446 (Out) is the strongest of the 4 non-duskside plume crossings, and
 436 hiss intensities during orbits 869, 939, and 977 are among the strongest in the 10 duskside
 437 plume crossings (see Figure 5 and Table 2). From Figure 8, and the corresponding figures
 438 for the other 10 plumes not shown, we deduce that at a fixed L -shell, τ_{loss} increases as the
 439 electron kinetic energy increases from 100 keV to 1 MeV. It is also evident from Figure 8
 440 that scattering by hiss in plumes can be especially effective for electrons of energy 100 -
 441 200 keV. For instance, for the plume in orbit 977 (panel (d)), for which the average wave
 442 amplitude $\overline{\Delta B} = 102$ pT, τ_{loss} ranges from 2.9 to 6.3 hr for 100 keV electrons, and from
 443 6.6 to 13.8 hr for 200 keV electrons. For the plume in orbit 939 (panel (c)), for which the
 444 wave intensity is strong ($\overline{\Delta B} = 203$ pT), the minimum loss timescale $(\tau_{loss})_{min}$ is 0.7 hr
 445 for 100 keV electrons and 1.1 hr for 200 keV electrons. For orbit 869 (panel (b), $\overline{\Delta B} = 34$
 446 pT), minimum timescales are $(\tau_{loss})_{min} = 15.2, 36.9$ hr for 100 keV, 200 keV electrons,
 447 and for orbit 446 (Out) (panel (a), $\overline{\Delta B} = 48$ pT) we find $(\tau_{loss})_{min} = 1.6, 3.7$ days for 100
 448 keV, 200 keV electrons.

449 We can also see from Figure 8 that, in general, scattering by hiss in plumes is somewhat
 450 less effective for 500 keV electrons, and still more ineffective for 1 MeV electrons. Minimum
 451 loss timescales for the plumes in orbits 977, 869, and 446 are respectively $(\tau_{loss})_{min} = 1,$

452 5.6, and 13 days, for 500 keV electrons. Corresponding respective values for 1 MeV
 453 electrons are $(\tau_{loss})_{min} = 3.1, 18, \text{ and } 41$ days. Particularly rapid scattering of 500 keV -
 454 1 MeV electrons by hiss in plumes is possible, but only in the case of intense waves, e.g.,
 455 for the plume in orbit 939, $(\tau_{loss})_{min} = 4.6$ hr for 500 keV electrons and $(\tau_{loss})_{min} = 15.4$
 456 hr for 1 MeV electrons.

457 In Figure 9 we plot the loss timescales for electrons of energy 100 keV, 200 keV, 500
 458 keV, and 1 MeV, as a function of L -shell, in the respective panels (a) - (d), for all the 14
 459 chosen plumes in our study. Complementary to Figure 9, we list in Table 3 the number
 460 of the chosen plumes for which electrons at each of the energies 100 keV, 200 keV, 500
 461 keV, and 1 MeV, have a loss timescale less than the specified values (0.1, 0.5, 1, and
 462 2 days) at some L -shells. Figure 9 and Table 3 essentially summarize the results of
 463 our calculations of τ_{loss} for our total selection of plumes. The decrease in efficiency of
 464 scattering by hiss as electron energies increase from 100 keV to 1 MeV is confirmed in
 465 Figure 9 by the general upward shift of the timescale profiles from panel (a) through to
 466 panel (d). Likewise, the number of profiles (or portions of profiles) located above $\tau_{loss} = 5$
 467 days, the nominal timescale above which scattering is ineffective in plumes, progressively
 468 increases from panel (a) through to panel (d). The degree of effectiveness of electron
 469 scattering by hiss at each of the energies 100 keV, 200 keV, 500 keV, and 1 MeV can
 470 be particularly appreciated by viewing each of the panels (a) - (d) of Figure 9 with each
 471 corresponding column of Table 3. For instance, for 100 keV electrons scattering is fairly
 472 rapid ($\tau_{loss} < 0.5$ day) at some L -shells in 6 of the 14 chosen plumes. Further, in 9
 473 plumes scattering of 100 keV electrons can be regarded as at least moderately effective
 474 ($\tau_{loss} < 2$ days) at some L -shells. It is also useful to examine the entries in each particular

row of Table 3 separately, e.g., the number of plumes for which $\tau_{loss} < 1$ day, at some L -shells, progressively decreases from 7 to 1 as the electron energy increases from 100 keV to 1 MeV. The scattering of MeV electrons in less than 1 day appears to require hiss amplitudes well in excess of 100 pT. Such a statement is not straightforward to qualify accurately, however, since τ_{loss} depends in a complicated way on the various parameters occurring in the formula for the diffusion coefficient (7).

Of the 14 chosen plumes, 6 contain at least reasonably intense hiss, specifically with an average wave amplitude satisfying $\overline{\Delta B} \geq 42$ pT (see Table 2). The plume in orbit 939, with $\overline{\Delta B} = 203$ pT, contains the most intense hiss. We have also selected 3 plumes with relatively weak hiss, satisfying $\overline{\Delta B} \leq 16$ pT. Electron scattering in these plumes (in orbits 297, 302, and 673) is naturally likewise weak, in general, with minimum values of τ_{loss} of at least several days.

Overall, it is clear from the numerical results reported in this section that, under appropriate conditions, hiss in plumes can induce significant precipitation losses of energetic (100 keV - 1 MeV) electrons in the outer zone, $3 < L < 7$.

5. Discussion

This is the first study to quantify the contribution of pitch-angle scattering by whistler-mode hiss in plumes to the total precipitation loss of outer-zone energetic electrons using experimental wave data in observed plumes. Understanding the acceleration and loss mechanisms of radiation belt electrons is needed to develop models for nowcasting and forecasting of relativistic (> 1 MeV) electrons that are a potential danger to satellites and humans in space. A primary objective of the twin-spacecraft NASA Radiation Belt Storm Probes (RBSP) mission [*Kintner et al.*, 2002] and the proposed Canadian Outer

497 Radiation Belt Injection, Transport, Acceleration and Loss Satellite (ORBITALS) mission
498 [*Mann et al.*, 2006] is to understand the physical processes that control the dynamical
499 variation of outer radiation belt electron fluxes. Wave-particle interactions undoubtedly
500 play a crucial role in radiation belt electron dynamics. Electron gyroresonance with
501 VLF chorus can lead to stochastic acceleration of seed (~ 100 keV) electrons to MeV
502 energies in the low density regions outside the plasmasphere and plasmaspheric plumes
503 [*Summers et al.*, 1998, 2002, 2004, 2007b; *Horne and Thorne*, 1998; *Roth et al.*, 1999;
504 *Summers and Ma*, 2000; *Meredith et al.*, 2002, 2003a; *Miyoshi et al.*, 2003; *Horne et al.*,
505 2005a, 2005b; *Varotsou et al.*, 2005; *Omura and Summers*, 2006; *Shprits et al.*, 2006b;
506 *Li et al.*, 2007]. Relativistic (> 1 MeV) electrons just outside the plasmopause can be
507 scattered by VLF chorus into the loss cone, on timescales of a day, and observed at
508 low altitudes as microburst precipitation [*Lorentzen et al.*, 2001; *Thorne et al.*, 2005].
509 Scattering by EMIC waves along the duskside plasmasphere can induce precipitation loss
510 of MeV electrons on timescales of several hours to a day [*Lorentzen et al.*, 2000; *Summers*
511 *and Thorne*, 2003; *Meredith et al.*, 2003b; *Summers et al.*, 2007b]. In the present study
512 we have shown that whistler-mode hiss in plumes can likewise induce precipitation loss
513 of MeV electrons in a day or less, though only in the case of exceptionally strong waves
514 (typically with amplitude 100's pT). Of particular interest in our study is the finding that
515 electrons of energy 100 - 200 keV, which are required to form a seed population from
516 which MeV electrons are generated, can suffer rapid precipitation loss (in a timescale
517 of hours) due to scattering by hiss in plumes. Thus, while scattering by hiss in plumes
518 may not usually induce rapid precipitation loss of MeV electrons, hiss scattering may
519 reduce the generation of MeV electrons by depleting the seed electron population. To

520 verify the latter process, quantitative modeling of the transport of seed electrons from
521 the plasmashet would be required. The general conclusion to our study is that pitch-
522 angle scattering by hiss in plumes in the frequency range $104 < f < 1040$ Hz can be
523 efficient for inducing precipitation loss of outer-zone electrons with energies throughout
524 the range 100 keV - 1 MeV. However, the results in section 4 show that the magnitude
525 of the precipitation loss timescale can be highly dependent on wave power, L -value, and
526 electron energy. Further, as we have pointed out above, pitch-angle scattering rates can
527 be sensitive to wave-normal angle and the latitudinal distributions of density and wave
528 power. Accordingly, the precipitation loss timescales computed in this paper could be
529 conservatively regarded as lower bounds.

530 The competition between acceleration and loss of energetic electrons is determined
531 by wave-particle interactions taking place outside and inside the dense thermal regions
532 comprising the plasmasphere and plasmaspheric plumes. Acceleration and loss of energetic
533 electrons due to gyroresonance with whistler-mode chorus take place outside these thermal
534 regions, while precipitation loss due to pitch-angle scattering by hiss and EMIC waves
535 takes place inside the thermal regions. The generation and global distribution of energetic
536 electrons in the outer zone is therefore greatly influenced by the distribution of thermal
537 plasma. Accurate modeling of the dynamical variation of the outer radiation belt electron
538 flux requires knowledge of the spectral intensity and temporal variation of the appropriate
539 wave modes both inside and outside the thermal plasma regions.

540 **Acknowledgments.** This work is supported by the Natural Sciences and Engineering
541 Research Council of Canada under grant A-0621. Additional support is acknowledged
542 from NSF grant ATM 0402615. Part of this project was carried out when D. S. was Visiting

543 Scholar in the Department of Physics and Technology, University of Bergen, Norway; D. S.
544 thanks the University of Bergen, and especially Finn Soraas, for the excellent hospitality.

References

- 545 Abel, B., and R. M. Thorne (1998), Electron scattering loss in Earth's inner magne-
546 sphere, 1. Dominant physical processes, *J. Geophys. Res.*, *103*, 2385.
- 547 Albert, J. M. (1994), Quasi-linear pitch angle diffusion coefficients: Retaining high har-
548 monics, *J. Geophys. Res.*, *99*, 23741.
- 549 Albert, J. M. (2003), Evaluation of quasi-linear diffusion coefficients for EMIC waves in
550 a multispecies plasma, *J. Geophys. Res.*, *108*(A6), 1249, doi:10.1029/2002JA009792.
- 551 Anderson, R. R., D. A. Gurnett, and D. L. Odem (1992), CRRES plasma wave experiment,
552 *J. Spacecr. Rockets*, *29*, 570.
- 553 Baker, D. N., S. G. Kanekal, X. Li, S. P. Monk, J. Goldstein, and J. L. Burch (2004),
554 An extreme distortion of the Van Allen belt arising from the Halloween solar storm in
555 2003, *Nature*, *432*, 878.
- 556 Burch, J. L. (2006), New insights on magnetospheric processes from IMAGE, *Conference*
557 *on Earth-Sun System Exploration: Energy Transfer*, Kona, Hawaii, USA, January 16-
558 20, 2006.
- 559 Burch, J. L., W. S. Lewis, T. J. Immel, P. C. Anderson, H. U. Frey, S. A. Fuselier,
560 J. C. Gerard, S. B. Mende, D. G. Mitchell, and M. F. Thomsen (2002), Interplanetary
561 magnetic field control of afternoon-sector detached proton auroral arcs, *J. Geophys.*
562 *Res.*, *107*(A9), 1251, doi:10.1029/2001JA007554.

- 563 Carpenter, D. L. (1963), Whistler evidence of a “knee” in the magnetospheric ionization
564 density profile, *J. Geophys. Res.*, *68*, 1675.
- 565 Carpenter, D. L., and C. G. Park (1973), On what ionospheric workers should know about
566 the plasmopause-plasmasphere, *Rev. Geophys.*, *11*(1), 133.
- 567 Carpenter, D. L., and R. R. Anderson (1992), An ISEE/whistler model of equatorial
568 electron density in the magnetosphere, *J. Geophys. Res.*, *97*, 1097.
- 569 Carpenter, D. L., and J. Lemaire (1997), Erosion and recovery of the plasmasphere in the
570 plasmopause region, *Space Sci. Rev.*, *80*, 153.
- 571 Chan, K. W., and R. E. Holzer (1976), ELF hiss associated with plasma density enhance-
572 ments in the outer magnetosphere, *J. Geophys. Res.*, *81*, 2267.
- 573 Chappell, C. R. (1974), Detached plasma regions in the magnetosphere, *J. Geophys. Res.*,
574 *79*, 1861.
- 575 Chappell, C. R., K. K. Harris, and G. W. Sharp (1970), The morphology of the bulge
576 region of the plasmasphere, *J. Geophys. Res.*, *75*, 3848.
- 577 Cornilleau-Wehrin, N., R. Gendrin, F. Lefeuvre, M. Parrot, R. Grard, D. Jones,
578 A. Bahnsen, E. Ungstrup, and W. Gibbons (1978), VLF electromagnetic waves ob-
579 served onboard GEOS-1, *Space Sci. Rev.*, *22*, 371.
- 580 Darrouzet, F., J. De Keyser, P. M. E. Decreau, D. L. Gallagher, V. Pierrard, J. F. Lemaire,
581 B. R. Sandel, I. Dandouras, H. Matsui, M. Dunlop, J. Cabrera, A. Masson, P. Canu,
582 J. G. Trotignon, J. L. Rauch, and M. Andre (2006), Analysis of plasmaspheric plumes:
583 CLUSTER and IMAGE observations, *Ann. Geophys.*, *24*, 1737.
- 584 Dent, Z. C., I. R. Mann, J. Goldstein, F. W. Menk, and L. G. Ozeke (2006), Plasmas-
585 pheric depletion, refilling, and plasmopause dynamics: A coordinated ground-based and

- 586 IMAGE satellite study, *J. Geophys. Res.*, *111*, A03205, doi:10.1029/2005JA011046.
- 587 Draganov, A. B., U. S. Inan, V. S. Sonwalker, and T. F. Bell (1992), Magnetospherically
588 reflected whistlers as a source of plasmaspheric hiss, *Geophys. Res. Lett.*, *19*, 233.
- 589 Etcheto, J., R. Gendrin, J. Solomon, and A. Roux (1973), A self-consistent theory of
590 magnetospheric ELF hiss, *J. Geophys. Res.*, *78*, 8150.
- 591 Ganguli, G., M. A. Reynolds, and M. W. Liemohn (2000), The plasmasphere and advances
592 in plasmaspheric research, *J. Atmos. Solar-Terr. Phys.*, *62*, 1647.
- 593 Goldstein, J. (2006), Plasmasphere response: tutorial and review of recent imaging results,
594 *Space Sci. Rev.*, doi:10.1007/s11214-006-9105-y.
- 595 Goldstein, J., B. R. Sandel, P. H. Reiff, and M. R. Hairston (2003), Control of plasmas-
596 pheric dynamics by both convection and sub-auroral polarization stream, *Geophys. Res.*
597 *Lett.*, *30*, 2243.
- 598 Goldstein, J., B. R. Sandel, M. F. Thomsen, M. Spasojevic, and P. H. Reiff (2004),
599 Simultaneous remote sensing and in situ observations of plasmaspheric drainage plumes,
600 *J. Geophys. Res.*, *109*, A03202, doi:10.1029/2003JA010281.
- 601 Goldstein, J., B. R. Sandel, W. T. Forrester, M. F. Thomsen, and M. R. Hairston
602 (2005), Global plasmasphere evolution 22 - 23 April 2001, *J. Geophys. Res.*, *110*, A12218,
603 doi:10.1029/2005JA011282.
- 604 Green, J. L., S. Boardsen, L. Garcia, W. W. L. Taylor, S. F. Fung, and B. W. Reinisch
605 (2005), On the origin of whistler mode radiation in the plasmasphere, *J. Geophys. Res.*,
606 *110*, A03201, doi:10.1029/2004JA010495.
- 607 Green, J. L., S. Boardsen, L. Garcia, S. F. Fung, and B. W. Reinisch (2006), Reply to
608 "Comment on "On the origin of whistler mode radiation in the plasmasphere" by Green

- 609 et al.”, *J. Geophys. Res.*, *111*, A09211, doi:10.1029/2006JA011622.
- 610 Hayakawa, M., and S. S. Sazhin (1992), Mid-latitude and plasmaspheric hiss: A review,
611 *Planet. Space Sci.*, *40*, 1325.
- 612 Hayakawa, M., N. Ohmi, M. Parrot, and F. Lefeuvre (1986), Direction finding of ELF
613 hiss emissions in a detached plasma region of the magnetosphere, *J. Geophys. Res.*, *91*,
614 135.
- 615 Horne, R. B., and R. M. Thorne (1998), Potential waves for relativistic electron scattering
616 and stochastic acceleration during magnetic storms, *Geophys. Res. Lett.*, *25*, 3011.
- 617 Horne, R. B., R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R.
618 Anderson (2005a), Timescale for radiation belt electron acceleration by whistler mode
619 chorus waves, *J. Geophys. Res.*, *110*, A03225, doi:10.1029/2004JA010811.
- 620 Horne, R. B., R. M. Thorne, Y. Y. Shprits, N. P. Meredith, S. A. Glauert, A. J. Smith,
621 S. G. Kanekal, D. N. Baker, M. J. Engebretson, J. L. Posch, M. Spasojevic, U. S. Inan,
622 J. S. Pickett, and P. M. E. Decreau (2005b), Wave acceleration of electrons in the Van
623 Allen radiation belts, *Nature*, *437*, 227, doi:10.1038/nature03939.
- 624 Horwitz, J. L., R. H. Comfort, and C. R. Chappell (1990), A statistical characterization
625 of plasmasphere structure and boundary locations, *J. Geophys. Res.*, *95*, 7937.
- 626 Huang, C. Y., C. K. Goertz, and R. R. Anderson (1983), A theoretical study of plasmas-
627 pheric hiss generation, *J. Geophys. Res.*, *88*, 7927.
- 628 Kintner, P. M., and the Living With a Star Geospace Mission Definition Team (2002), The
629 LWS geospace storm investigations: Exploring the extremes of space weather, *NASA*
630 *Tech. Memo.*, *TM-2002-211613*.

- 631 Lemaire, J. F., and K. I. Gringauz (1998), *The Earth's Plasmasphere*, Cambridge Univer-
632 sity Press, New York.
- 633 Li, W., Y. Y. Shprits, and R. M. Thorne (2007), Dynamic evolution of energetic outer
634 zone electrons due to wave-particle interactions during storms, *J. Geophys. Res.*, *112*,
635 A10220, doi:10.1029/2007JA012368.
- 636 Lorentzen, K. R., M. P. McCarthy, G. K. Parks, J. E. Foat, R. M. Millan, D. M. Smith,
637 R. P. Lin, and J. P. Treilhou (2000), Precipitation of relativistic electrons by interaction
638 with electromagnetic ion cyclotron waves, *J. Geophys. Res.*, *105*, 5381.
- 639 Lorentzen, K. R., J. B. Blake, U. S. Inan, and J. Bortnik (2001), Observations of rel-
640 ativistic electron microbursts in association with VLF chorus, *J. Geophys. Res.*, *106*,
641 6017.
- 642 Lyons, L. R., and R. M. Thorne (1973), Equilibrium structure of radiation belt electrons,
643 *J. Geophys. Res.*, *78*, 2142.
- 644 Lyons, L. R., R. M. Thorne, and C. F. Kennel (1972), Pitch-angle diffusion of radiation
645 belt electrons within the plasmasphere, *J. Geophys. Res.*, *77*, 3455.
- 646 Mann, I. R., K. G. Balmain, J. B. Blake, D. Boteler, S. Bourdarie, J. H. Clemmons, Z. C.
647 Dent, A. W. Degeling, R. Fedosejeves, J. F. Fennell, B. J. Fraser, J. C. Green, V. K.
648 Jordanova, A. Kale, L. M. Kistler, D. J. Knudsen, M. R. Lessard, T. M. Loto'aniu,
649 D. K. Milling, T. P. O'Brien, T. G. Onsager, L. G. Ozeke, I. J. Rae, R. Rankin, G. D.
650 Reeves, A. J. Ridley, G. J. Sofko, D. Summers, I. Thomson, R. M. Thorne, Y. Y. Tsui,
651 C. Unick, D. Vassiliadis, J. R. Wygant, and A. W. Yau (2006), The Outer Radiation
652 Belt Injection, Transport, Acceleration and Loss Satellite (ORBITALS): A Canadian
653 small satellite mission for ILWS, *Adv. Space Res.*, *38*, 1838.

- 654 Masson, A., U. S. Inan, H. Laakso, O. Santolik, and P. Decreau (2004), Cluster observa-
655 tions of mid-latitude hiss near the plasmopause, *Ann. Geophys.*, *22*, 2565.
- 656 Meredith, N. P., R. B. Horne, D. Summers, R. M. Thorne, R. H. A. Iles, D. Heynder-
657 ickx, and R. R. Anderson (2002), Evidence for acceleration of outer zone electrons to
658 relativistic energies by whistler mode chorus, *Ann. Geophys.*, *20*, 967.
- 659 Meredith, N. P., M. Cain, R. B. Horne, R. M. Thorne, D. Summers, and R. R. An-
660 derson (2003a), Evidence for chorus-driven electron acceleration to relativistic energies
661 from a survey of geomagnetically disturbed periods, *J. Geophys. Res.*, *108*(A6), 1248,
662 doi:10.1029/2002JA009764.
- 663 Meredith, N. P., R. M. Thorne, R. B. Horne, D. Summers, B. J. Fraser, and R. R.
664 Anderson (2003b), Statistical analysis of relativistic electron energies for cyclotron
665 resonance with EMIC waves observed on CRRES, *J. Geophys. Res.*, *108*(A6), 1250,
666 doi:10.1029/2002JA009700.
- 667 Meredith, N. P., R. B. Horne, R. M. Thorne, D. Summers, and R. R. Anderson
668 (2004), Substorm dependence of plasmaspheric hiss, *J. Geophys. Res.*, *109*, A06209,
669 doi:10.1029/2004JA010387.
- 670 Meredith, N. P., R. B. Horne, S. A. Glauert, R. M. Thorne, D. Summers, J. M. Albert,
671 and R. R. Anderson (2006a), Energetic outer zone electron loss timescales during low
672 geomagnetic activity, *J. Geophys. Res.*, *111*, A05212, doi:10.1029/2005JA011516.
- 673 Meredith, N. P., R. B. Horne, M. A. Clilverd, D. Horsfall, R. M. Thorne, and R. R.
674 Anderson (2006b), Origins of plasmaspheric hiss, *J. Geophys. Res.*, *111*, A09217,
675 doi:10.1029/2006JA011707.

- 676 Miyoshi, Y., A. Morioka, T. Obara, H. Misawa, T. Nagai, and Y. Kasahara (2003),
677 Rebuilding process of the outer radiation belt during the 3 November 1993 mag-
678 netic storm: NOAA and Exos-D observations, *J. Geophys. Res.*, *108*(A1), 1004,
679 doi:10.1029/2001JA007542.
- 680 Moldwin, M. B., M. F. Thomsen, S. J. Bame, D. J. McComas, and K. R. Moore (1994),
681 An examination of the structure and dynamics of the outer plasmasphere using multiple
682 geosynchronous satellites, *J. Geophys. Res.*, *99*(A6), 11475.
- 683 Moldwin, M. B., L. Downward, H. K. Rassoul, R. Amin, and R. R. Anderson (2002),
684 A new model of the location of the plasmopause: CRRES results, *J. Geophys. Res.*,
685 *107*(A11), 1339, doi:10.1029/2001JA009211.
- 686 Moldwin, M. B., J. Howard, J. Sanny, J. D. Bocchicchio, H. K. Rassoul, and R. R.
687 Anderson (2004), Plasmaspheric plumes: CRRES observations of enhanced density
688 beyond the plasmopause, *J. Geophys. Res.*, *109*, A05202, doi:10.1029/2003JA010320.
- 689 Omura, Y., and D. Summers (2006), Dynamics of high-energy electrons interacting with
690 whistler mode chorus emissions in the magnetosphere, *J. Geophys. Res.*, *111*, A09222,
691 doi:10.1029/2006JA011600.
- 692 Parrot, M., and F. Lefeuvre (1986), Statistical study of the propagation characteristics of
693 ELF hiss observed on GEOS-1, inside and outside the plasmasphere, *Ann. Geophys.*, *4*,
694 363.
- 695 Roth, I., M. Temerin, and M. K. Hudson (1999), Resonant enhancement of relativistic
696 electron fluxes during geomagnetically active periods, *Ann. Geophys.*, *17*, 631.
- 697 Sandel, B. R., J. Goldstein, D. L. Gallagher, and M. Spasojevic (2003), Extreme Ultravi-
698 olet Imager observations of the structure and dynamics of the plasmasphere, *Space Sci.*

699 *Rev.*, *109*, 25.

700 Santolik, O., M. Parrot, L. R. O. Storey, J. S. Pickett, and D. A. Gurnett (2001), Prop-
701 agation analysis of plasmaspheric hiss using Polar PWI measurements, *Geophys. Res.*
702 *Lett.*, *28*, 1127.

703 Sheeley, B. W., M. B. Moldwin, H. K. Rassoul, and R. R. Anderson (2001), An empirical
704 plasmasphere and trough density model: CRRES observations, *J. Geophys. Res.*, *106*,
705 25,631.

706 Shprits, Y. Y., W. Li, and R. M. Thorne (2006a), Controlling effect of the pitch angle
707 scattering rates near the edge of the loss cone on electron lifetimes, *J. Geophys. Res.*,
708 *111*, A12206, doi:10.1029/2006JA011758.

709 Shprits, Y. Y., R. M. Thorne, R. B. Horne, S. A. Glauert, M. Cartwright, C. T. Russell,
710 D. N. Baker, and S. G. Kanekal (2006b), Acceleration mechanism responsible for the
711 formation of the new radiation belt during the 2003 Halloween solar storm, *Geophys.*
712 *Res. Lett.*, *33*, L05104, doi:10.1029/2005GL024256.

713 Singer, H. J., W. P. Sullivan, P. Anderson, F. Mozer, P. Harvey, J. Wygant, and W. McNeil
714 (1992), Fluxgate magnetometer instrument on the CRRES, *J. Spacecr. Rockets*, *29*, 599.

715 Smith, E. J., A. M. A. Frandsen, B. T. Tsurutani, R. M. Thorne, and K. W. Chan (1974),
716 Plasmaspheric hiss intensity variations during magnetic storms, *J. Geophys. Res.*, *79*,
717 2507.

718 Sonwalkar, V. S., and U. S. Inan (1989), Lightning as an embryonic source of VLF hiss,
719 *J. Geophys. Res.*, *94*, 6986.

720 Spasojevic, M., J. Goldstein, D. L. Carpenter, U. S. Inan, B. R. Sandel, M. B. Moldwin,
721 and B. W. Reinisch (2003), Global response of the plasmasphere to a geomagnetic

- 722 disturbance, *J. Geophys. Res.*, *108*(A9), 1340, doi:10.1029/2003JA009987.
- 723 Spasojevic, M., H. U. Frey, M. F. Thomsen, S. A. Fuselier, S. P. Gary, B. R. Sandel, and
724 U. S. Inan (2004), The link between a detached subauroral proton arc and a plasmas-
725 pheric plume, *Geophys. Res. Lett.*, *31*, L04803, doi:10.1029/2003GL018389.
- 726 Summers, D. (2005), Quasi-linear diffusion coefficients for field-aligned electromag-
727 netic waves with applications to the magnetosphere, *J. Geophys. Res.*, *110*, A08213,
728 doi:10.1029/2005JA011159.
- 729 Summers, D., and C. Ma (2000), A model for generating relativistic electrons in the
730 Earth's inner magnetosphere based on gyroresonant wave-particle interactions, *J. Geo-
731 phys. Res.*, *105*, 2625.
- 732 Summers, D., and R. M. Thorne (2003), Relativistic electron pitch-angle scattering by
733 electromagnetic ion cyclotron waves during geomagnetic storms, *J. Geophys. Res.*,
734 *108*(A4), 1143, doi:10.1029/2002JA009489.
- 735 Summers, D., R. M. Thorne, and F. Xiao (1998), Relativistic theory of wave-particle
736 resonant diffusion with application to electron acceleration in the magnetosphere, *J.
737 Geophys. Res.*, *103*, 20,487.
- 738 Summers, D., C. Ma, N. P. Meredith, R. B. Horne, R. M. Thorne, D. Heynderickx, and
739 R. R. Anderson (2002), Model of the energization of outer-zone electrons by whistler-
740 mode chorus during the October 9, 1990 geomagnetic storm, *Geophys. Res. Lett.*, *29*(4),
741 2174, doi:10.1029/2002GL016039.
- 742 Summers, D., C. Ma, N. P. Meredith, R. B. Horne, R. M. Thorne, and R. R. Ander-
743 son (2004), Modeling outer-zone relativistic electron response to whistler-mode chorus
744 activity during substorms, *J. Atmos. Sol. Terr. Phys.*, *66*, 133.

745 Summers, D., B. Ni, and N. P. Meredith (2007a), Timescales for radiation belt electron
746 acceleration and loss due to resonant wave-particle interactions: 1. Theory, *J. Geophys.*
747 *Res.*, *112*, A04206, doi:10.1029/2006JA011801.

748 Summers, D., B. Ni, and N. P. Meredith (2007b), Timescales for radiation belt elec-
749 tron acceleration and loss due to resonant wave-particle interactions: 2. Evalua-
750 tion for VLF chorus, ELF hiss, and EMIC waves, *J. Geophys. Res.*, *112*, A04207,
751 doi:10.1029/2006JA011993.

752 Taylor Jr., H. A., J. M. Grebowsky, and W. J. Walsh (1971), Structured variations of the
753 plasmopause: evidence of a corotating plasma tail, *J. Geophys. Res.*, *76*, 6806.

754 Thorne, R. M., E. J. Smith, R. K. Burton, and R. E. Holzer (1973), Plasmaspheric hiss,
755 *J. Geophys. Res.*, *78*, 1581.

756 Thorne, R. M., E. J. Smith, K. J. Fiske, and S. R. Church (1974), Intensity variation of
757 ELF hiss and chorus during isolated substorms, *Geophys. Res. Lett.*, *1*, 193.

758 Thorne, R. M., S. R. Church, and D. J. Gorney (1979), On the origin of plasmaspheric
759 hiss: The importance of wave propagation and the plasmopause, *J. Geophys. Res.*, *84*,
760 5241.

761 Thorne, R. M., T. P. O'Brien, Y. Y. Shprits, D. Summers, and R. B. Horne (2005),
762 Timescale for MeV electron microburst loss during geomagnetic storms, *J. Geophys.*
763 *Res.*, *110*, A09202, doi:10.1029/2004JA010882.

764 Thorne, R. M., R. B. Horne, and N. P. Meredith (2006), Comment on "On the origin of
765 whistler mode radiation in the plasmasphere" by Green et al., *J. Geophys. Res.*, *111*,
766 A09210, doi:10.1029/2005JA011477.

- 767 Tsurutani, B. T., E. J. Smith, and R. M. Thorne (1975), Electromagnetic hiss and rela-
768 tivistic electron losses in the inner zone, *J. Geophys. Res.*, *80*, 600.
- 769 Varotsou, A., D. Boscher, S. Bourdarie, R. B. Horne, S. A. Glauert, and N. P. Meredith
770 (2005), Simulation of the outer radiation belt electrons near geosynchronous orbit in-
771 cluding both radial diffusion and resonant interaction with whistler-mode chorus waves,
772 *Geophys. Res. Lett.*, *32*, L19106, doi:10.1029/2005GL023282.

ORBIT	UT (start)	UT (end)	MLT (start)	MLT (end)	L (start)	L (end)	MLAT (start)	MLAT (end)
297 (In)	01:58	04:02	03:55	05:44	6.43	4.18	12.8	7.1
302 (Out)	22:01	23:35	23:17	01:28	3.26	5.86	15.4	16.3
446 (Out)	00:31	01:15	21:22	22:18	4.41	5.63	26.7	23.7
446 (In)	05:22	07:16	01:06	02:47	6.72	4.76	13.8	6.75
605 (Out)	05:03	06:43	19:14	20:45	4.15	6.05	4.9	-2.6
672 (Out)	15:33	15:48	18:14	18:33	4.45	4.85	-8.5	-9.9
673 (Out)	00:53	01:26	17:35	18:25	3.55	4.45	6.7	3.3
674 (Out)	11:08	11:48	18:09	18:55	4.45	5.55	-15.4	-18.5
810 (Out)	17:30	19:23	15:54	17:43	4.15	6.25	-6.0	-9.0
869 (Out)	00:54	02:46	16:07	17:14	5.65	6.85	-13.9	-14.5
871 (Out)	20:33	22:44	15:05	16:54	4.25	6.35	-7.1	-7.4
939 (Out)	01:12	02:16	13:49	14:48	4.95	6.15	-20.2	-18.8
941 (Out)	21:31	22:26	13:25	14:30	4.05	5.25	-11.8	-10.3
977 (Out)	09:30	11:00	13:06	14:16	5.85	6.65	-21.8	-17.7

Table 1. Specification of the 14 CRRES plume crossings chosen in this study. The magnetic latitude (MLAT) is given in degrees; UT is universal time and MLT is magnetic local time.

ORBIT	297	302	446 (Out)	446 (In)	605	672	673	674	810	869	871	939	941	977
$\overline{\Delta B}$ (pT)	14	16	48	27	42	25	13	37	91	34	60	203	31	102

Table 2. Average hiss amplitude $\overline{\Delta B}$ (pT) calculated by averaging the measured spectral intensity along each chosen plume crossing.

	100 keV	200 keV	500 keV	1 MeV
$\tau_{loss} < 2$ day (some L)	9	7	3	1
$\tau_{loss} < 1$ day (some L)	7	5	2	1
$\tau_{loss} < 0.5$ day (some L)	6	2	1	0
$\tau_{loss} < 0.1$ day (some L)	1	1	0	0

Table 3. Entries in the table indicate the number of the 14 chosen plumes for which electrons at the indicated energy have a loss timescale less than the specified value at some L -shells.

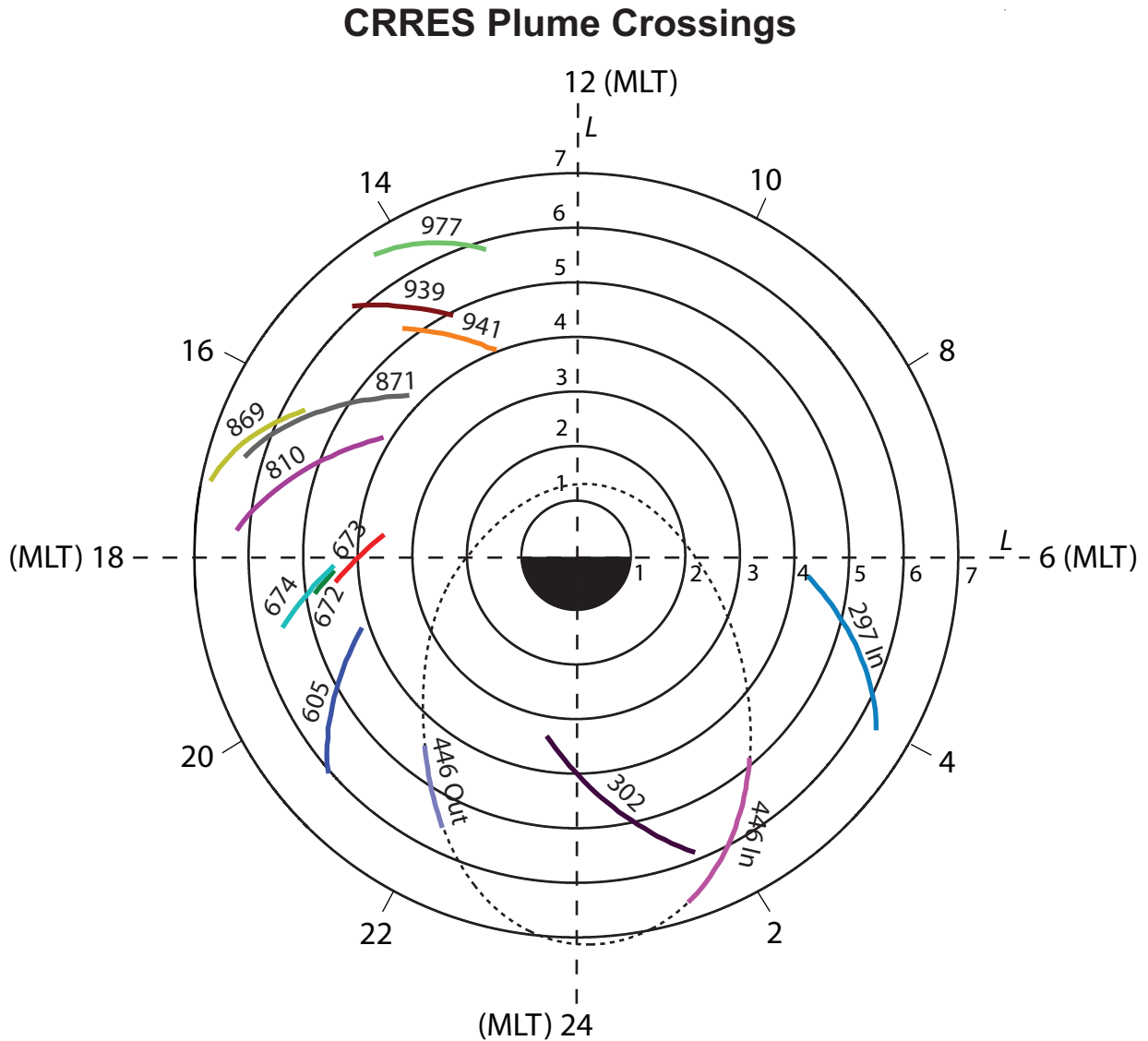


Figure 1. Diagram showing the 14 CRRES plume crossings identified by orbit number, chosen in this study. All the chosen plumes correspond to outbound portions of the specified orbits, except for the indicated 297 (In) and 446 (In) inbound crossings. Also shown is an approximate trajectory for CRRES orbit 446.

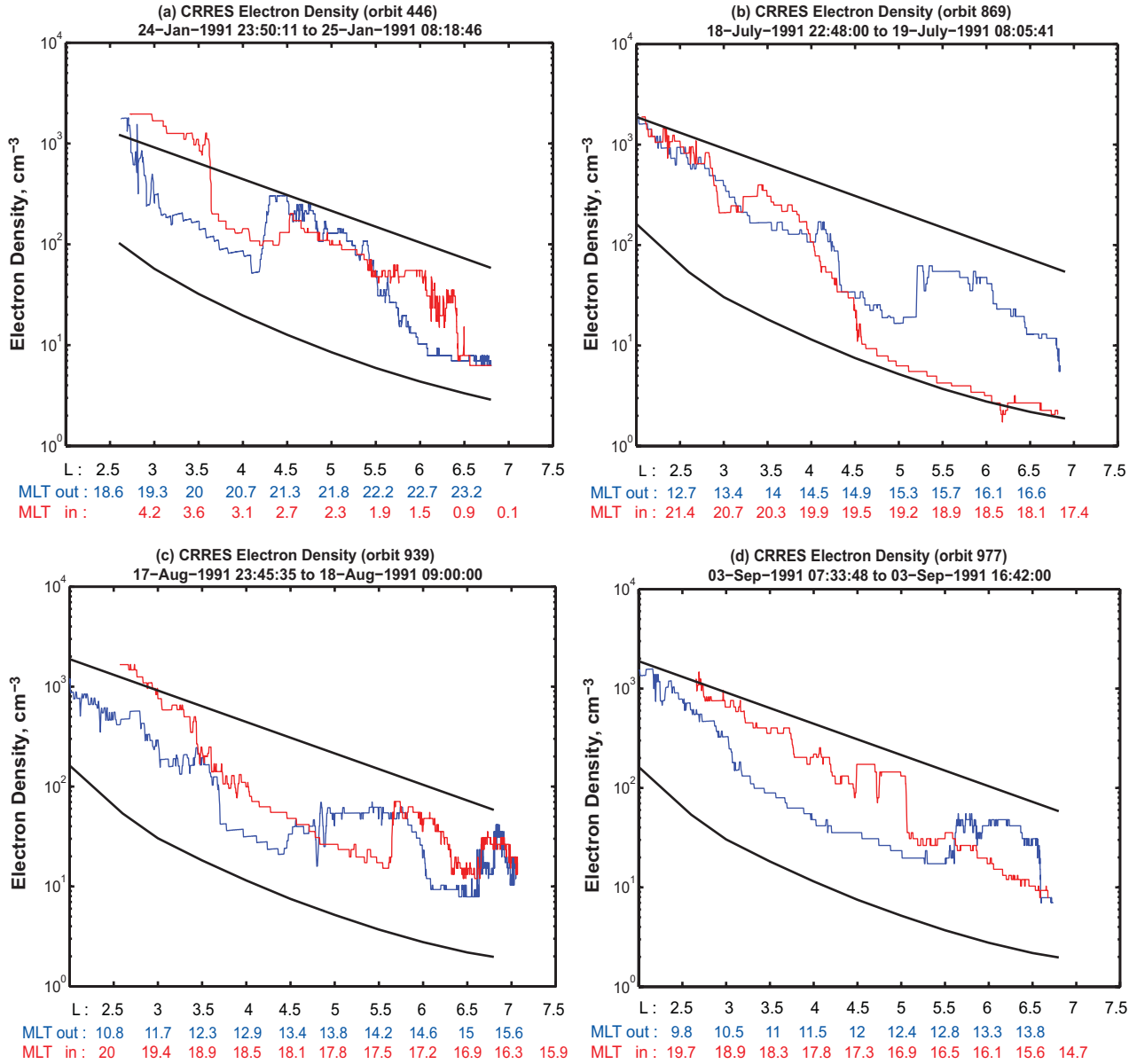


Figure 2. Measured CRRES electron density profiles for orbits 446, 869, 939, and 977. Chosen plume intervals during these orbits are specified in Table 1. The upper and lower black curves in each panel are model profiles of the saturated plasmasphere density and trough density due to *Carpenter and Anderson* [1992].

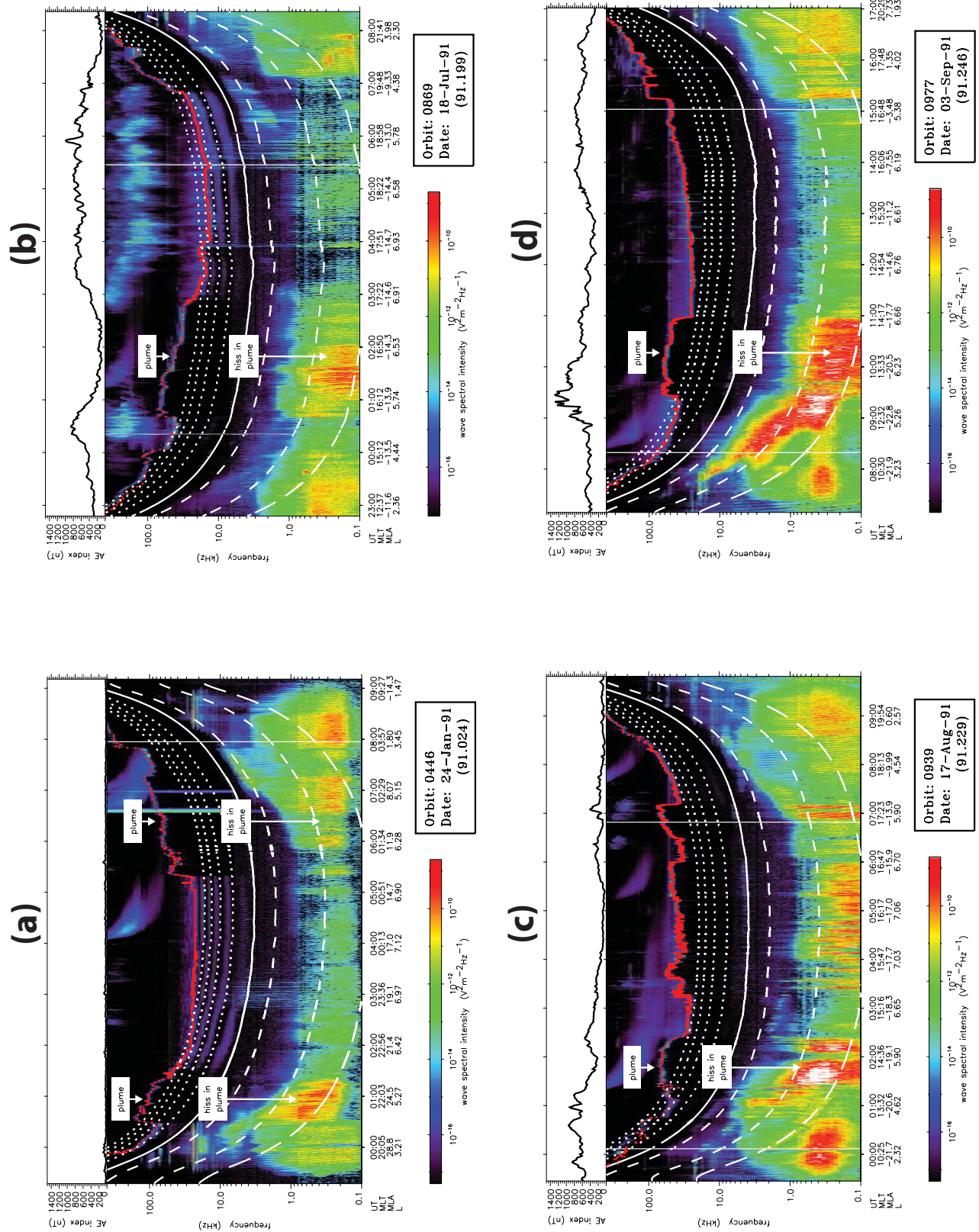


Figure 3. Survey plot of the wave spectral intensities observed on CRRES for orbits 446, 869, 939, and 977 in the respective panels (a), (b), (c), and (d).

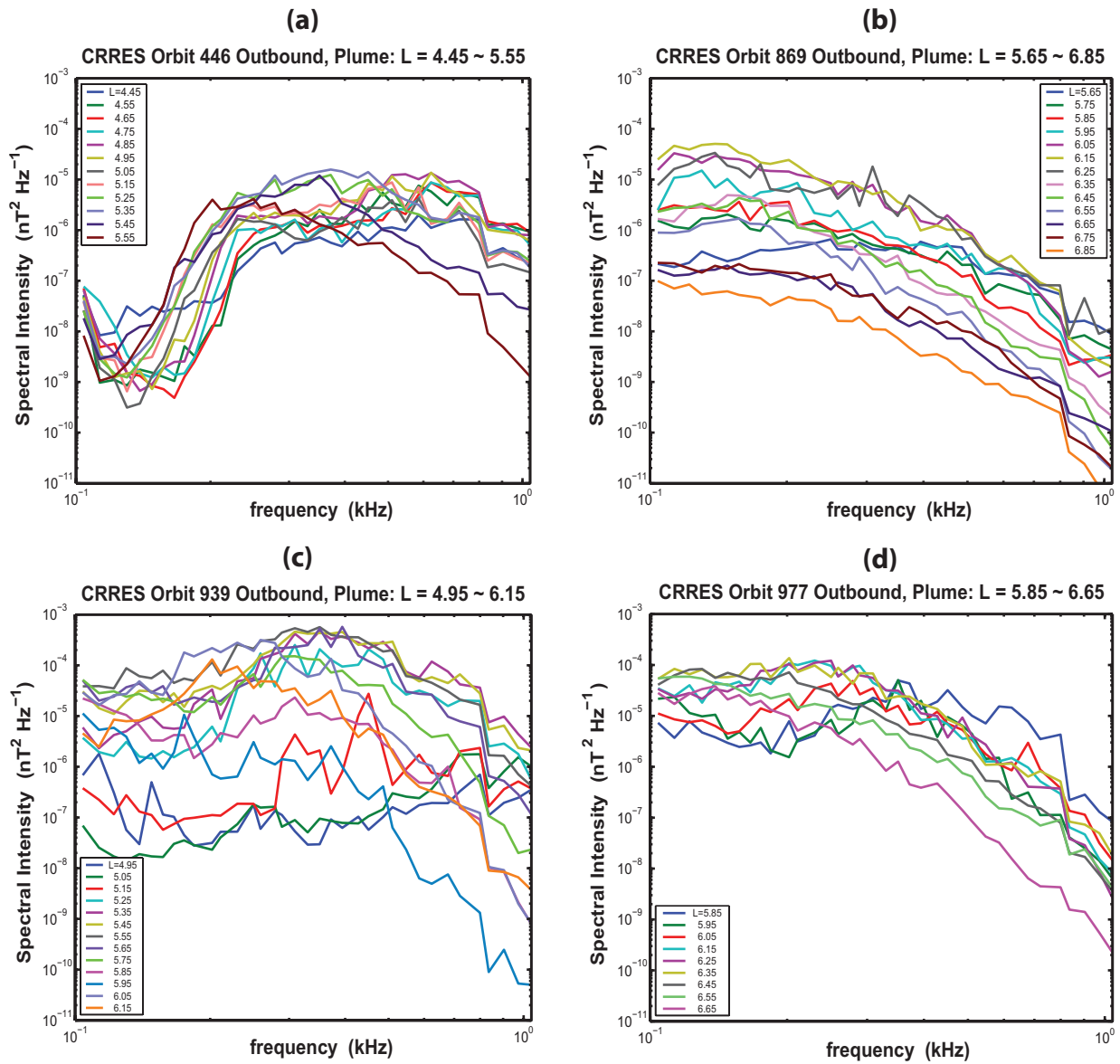


Figure 4. Corresponding to Figure 3, measured hiss spectral intensities at the indicated L -values during the chosen plume crossings from CRRES orbits 446 (Out), 869, 939, and 977.

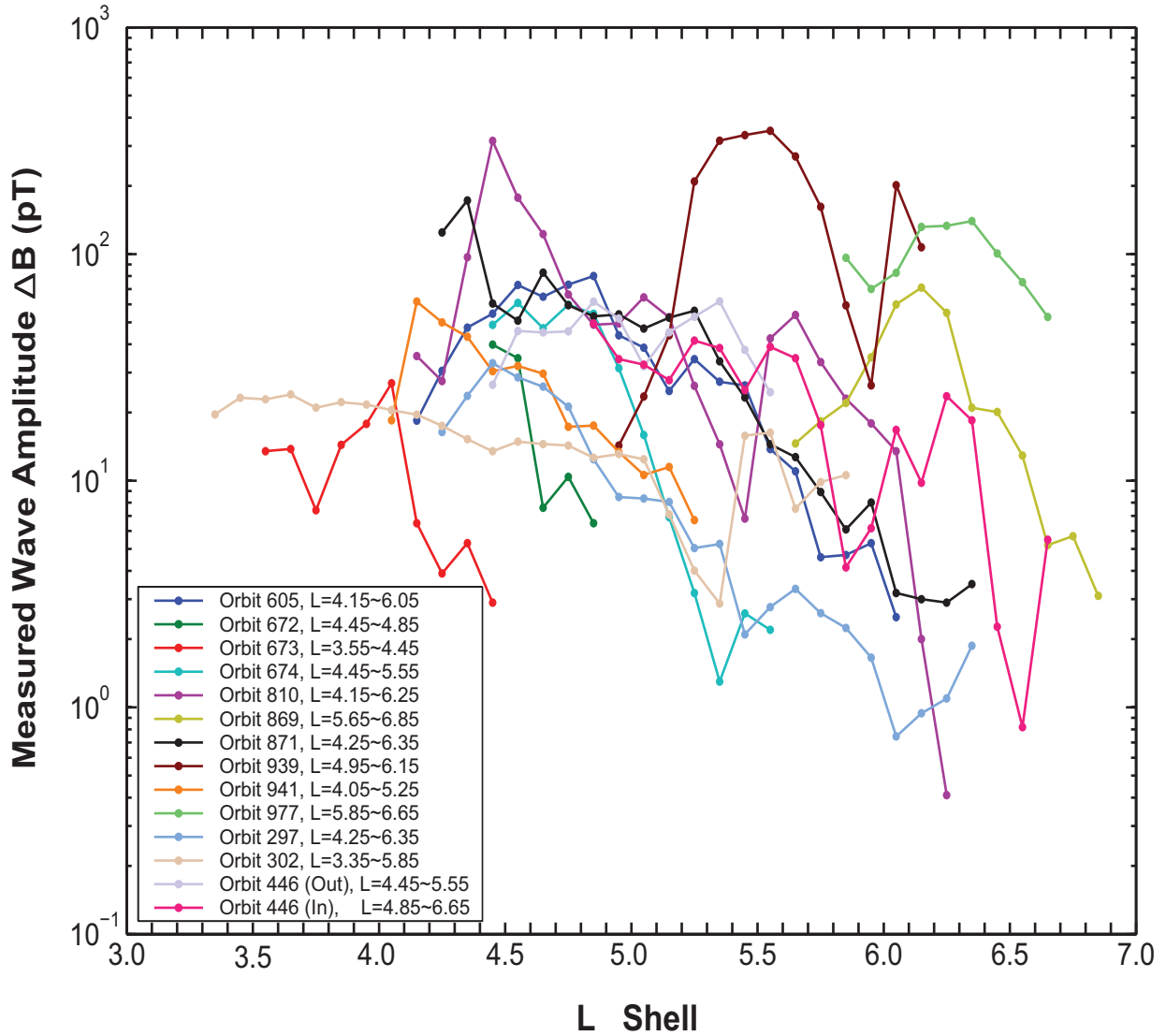


Figure 5. Local hiss amplitude in the frequency range 104 - 1040 Hz measured by CRRES along each chosen plume crossing.

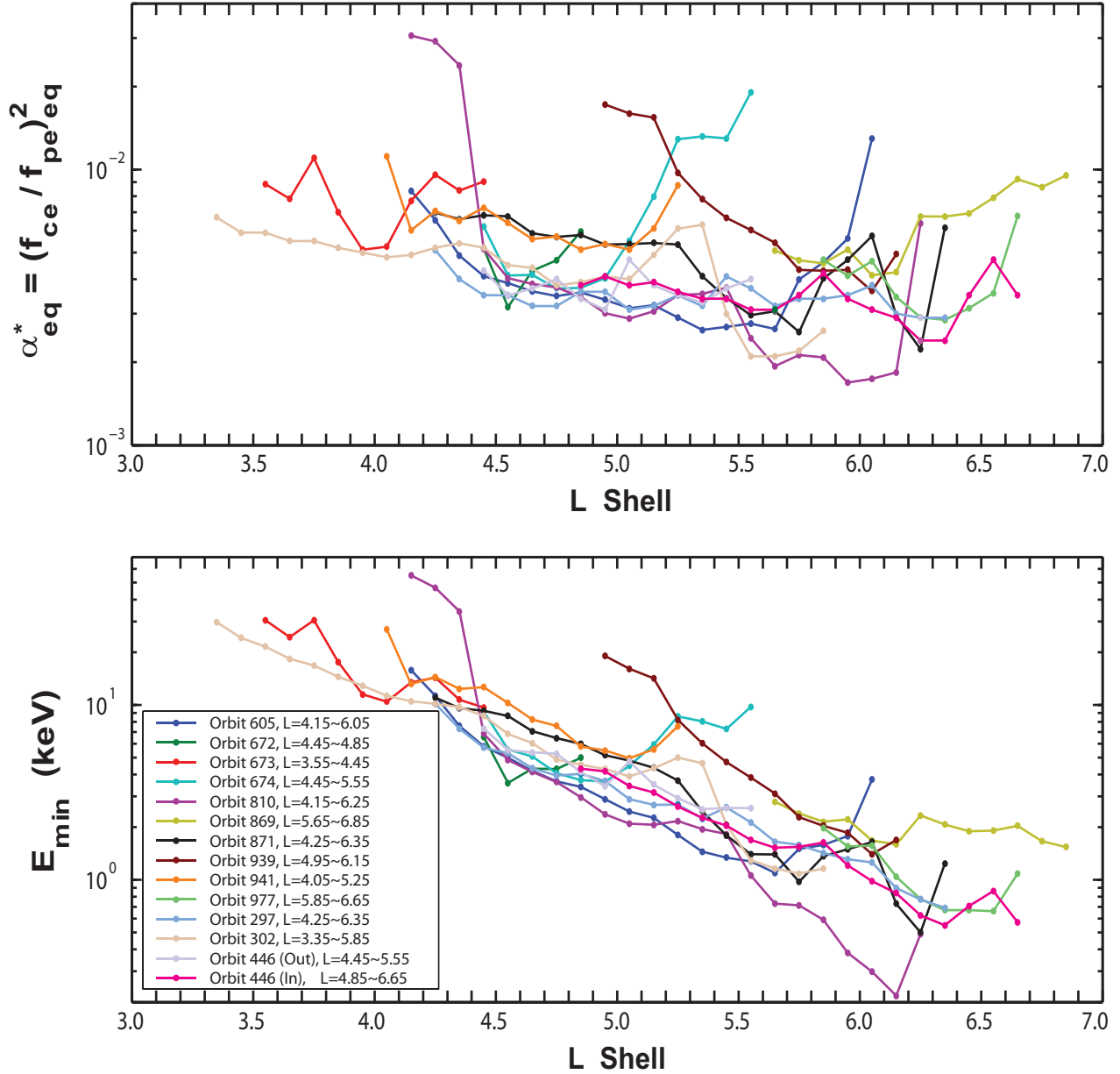


Figure 6. Variation of the equatorial value of the parameter $\alpha^* = (f_{ce}/f_{pe})^2$ with L -value, for the specified plume intervals, inferred from local observed values of f_{ce} and f_{pe} (top panel). In the bottom panel, we show minimum energies for electron resonance with hiss at the frequency 1040 Hz, as a function of L -value, calculated using the values of α^* given in the top panel.

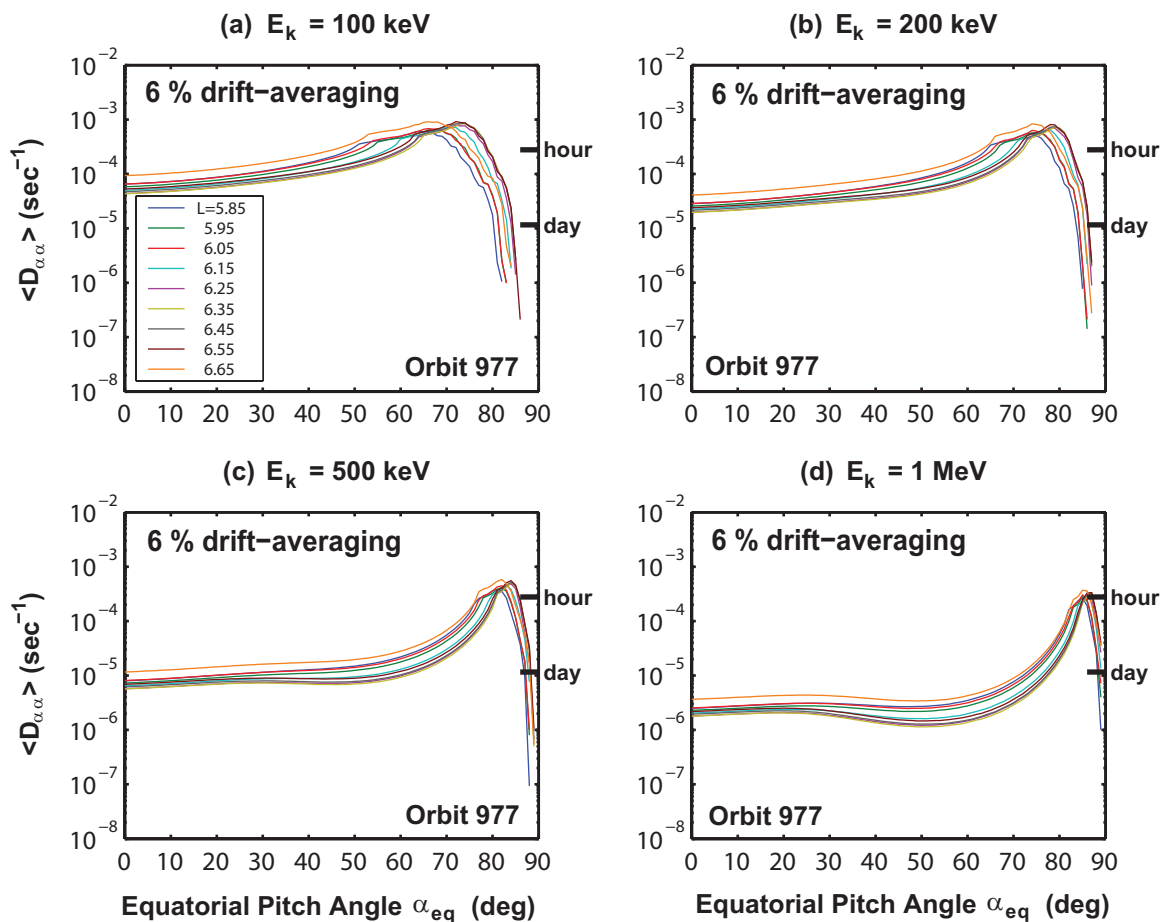


Figure 7. Bounce-averaged pitch-angle diffusion rates for electrons interacting with hiss during the chosen plume crossing for orbit 977, at the indicated L -values and electron energies. Hiss in the plume is assumed to be distributed along the whole field line.

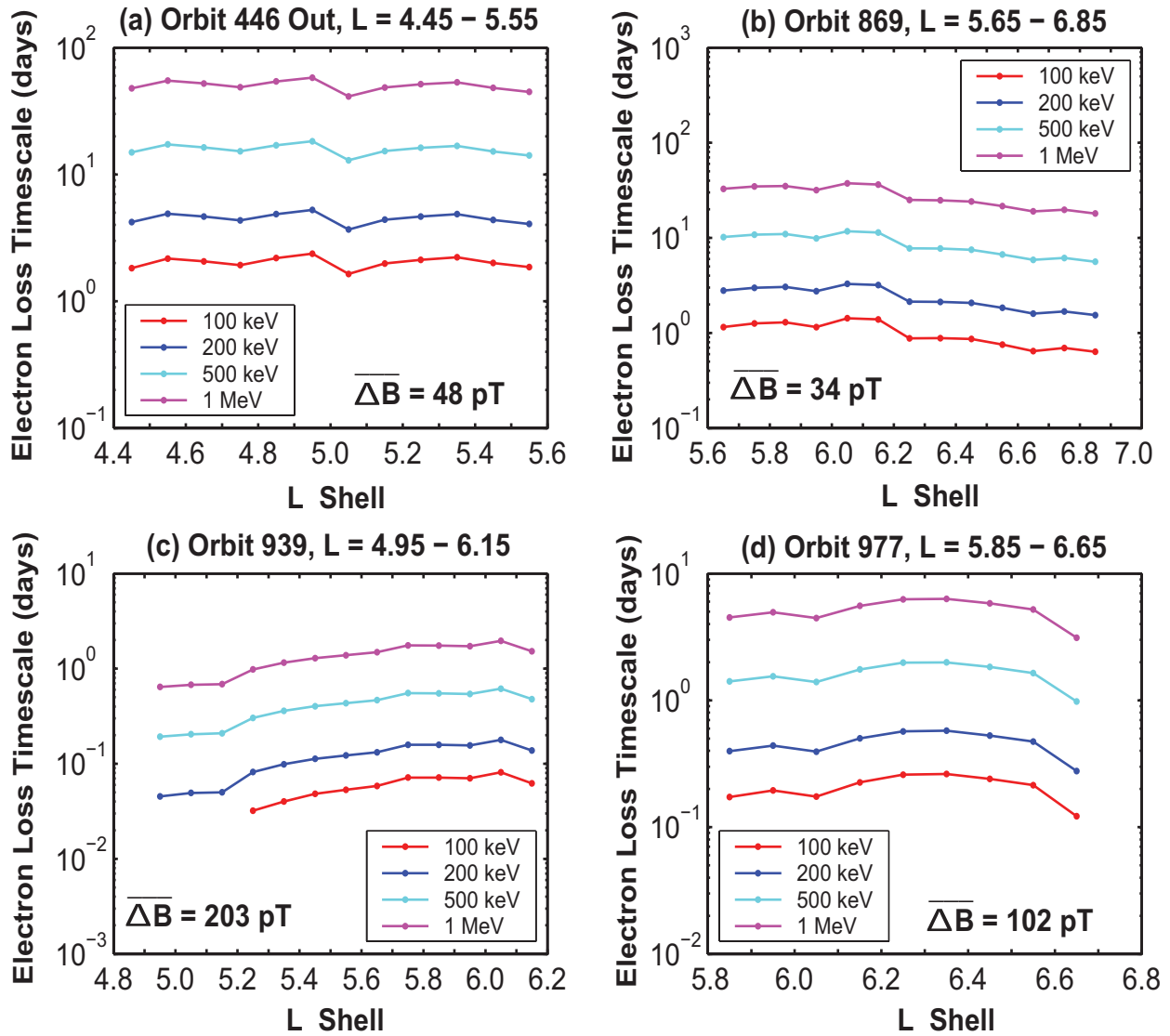


Figure 8. Electron loss timescales due to scattering by hiss at the specified energies, for the indicated CRRES plume crossings, as a function of L -value; 6 % drift-averaging has been applied.

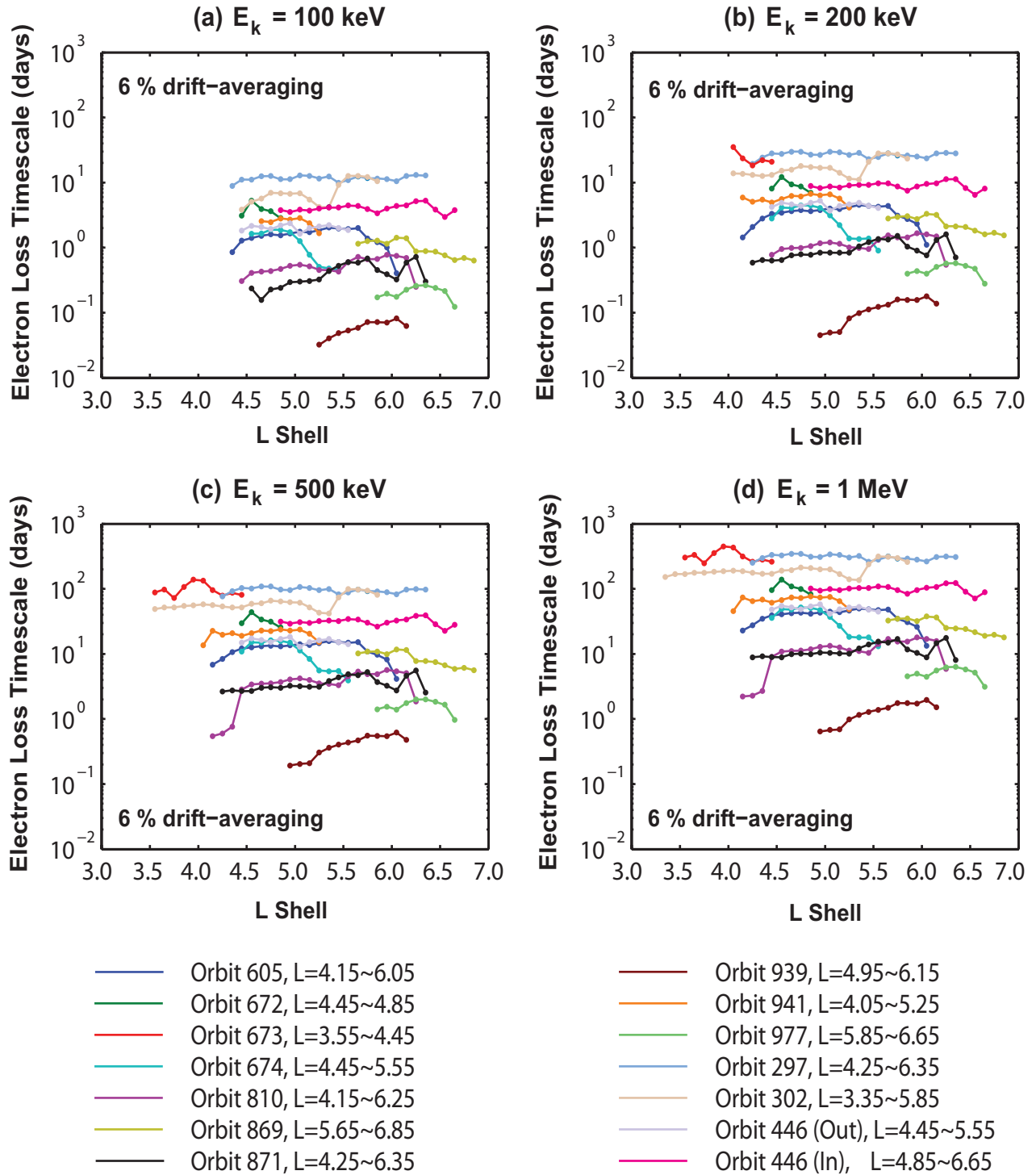


Figure 9. Summary plot of electron loss timescales due to scattering by hiss at the specified energies, for each of the 14 chosen CRRES plume crossings, as a function of L -value.