Spectral characteristics of the plasma dispersionless injection during the storm recovery phase on 11 March 1998

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[1] A substorm dispersionless injection event observed during the storm recovery phase on 11 March 1998 at geosynchronous orbit is carefully studied. The event shows the notable characteristics that for energetic ions the flux enhancement ratio before and after injection increases and remains elevated with increasing energy, while for energetic electrons it tends to decrease with increasing energy. In order to explain the unique injection feature, the authors propose a possible mechanism that velocity space diffusion adjusts the particle injection state. Spectral characteristics of four different phases (pregrowth phase, the growth phase, the substorm expansion phase, and the recovery phase) have been investigated. The differential fluxes of electrons from 50 keV to 1.5 MeV and ions from 50 keV to 1.2 MeV measured by Synchronous Orbit Plasma Analyzer (SOPA) instrument onboard LANL satellite 1991–080 are found to be best fitted with the three-parameter kappa distribution function (\(f \sim A_0 \cdot E^{[1 + E / (\kappa E_0)]^{-k-1}}\)) by Levenberg-Marquardt and Universal Global Optimization methods. The evolutions of the three parameters in the above kappa distribution in different substorm phases have been depicted for both electrons and ions. In each phase, \(E_0\) and \(k\) show an approximately linear relationship \(\kappa(E_0) = \kappa_0 + \eta E_0\). This linear relationship can be obtained by solving the velocity space diffusion equation with an initial superthermal kappa distribution. Ion and electron are found to have opposite trend of parameters \(\kappa_0\) and \(\eta\) in each phase, which indicates that the different species of particles exert different velocity space diffusion processes so that their flux enhancement ratios before and after injection are rather different. This implies that not only electric field acceleration, but also velocity space diffusion plays a very important role in the particle injection.


1. Introduction

[2] The differential energy spectra of plasma sheet ions and electrons can be described by the Maxwellian [Vasyliunas, 1971], the kappa [Christon et al., 1988] and the velocity exponential [Gloeckler et al., 1984]. The kappa and velocity exponential distributions both provide reasonable fits above 200 eV, while at high energies the observed spectra are more often similar to the kappa than to the velocity exponential forms [Christon et al., 1988]. The kappa distribution function takes the form of \(f \sim E^{[1 + E / (\kappa E_0)]^{-k-1}}\), where \(f\) is the differential flux, \(\langle cm^{-2} s^{-1} sr^{-1} \rangle\), \(E\) is particle energy in keV, \(E_0\) is the characteristic energy in keV and \(k\) is the power law index, which converges to Maxwellian as \(k \rightarrow \infty\), becomes a nearly Maxwellian form at low kinetic energies for \(E \leq E_0\) and a power law at high energies for \(E \gg E_0\). The kappa distribution function has been observed throughout the heliosphere: in the solar wind [Collier et al., 1996], the evening sector of the magnetosphere [Vasyliunas, 1968], the terrestrial plasma sheet [Christon et al., 1989], Jupiter’s magnetosphere [Kane et al., 1992] and Saturn’s magnetosphere [Krimigis et al., 1983]. Some papers have previously addressed the origin of the kappa distributions. For instance, Hasegawa et al. [1985] found that plasma immersed in a superthermal radiation field suffers enhanced velocity space diffusion resulting in a kappa distribution. Collier [1993] used a random walk in velocity space with jump lengths obeying a power law or Lévy flight probability distribution to produce a kappa-like distribution functions. Therefore, the existence of these non-Maxwellian distributions may have important implications both theoretically [Summers...
and Thorne, 1991] and in the analysis of space measurement data [Vasyliunas, 1971].

[5] Particle spectra can be formed by adiabatic (conservation of the first and the second adiabatic invariants for particles gyrating and bouncing along magnetic field lines) [Collier, 1995] and by nonadiabatic processes (e.g., acceleration, energy losses and particle drift and diffusion). Betatron and Fermi acceleration have been modeled for substorm injection by the inductive electric field and agree well with the observations [Li et al., 1998; Zaharia et al., 2004]. Pisarenko et al. [2002] have found that the nonconservation of the adiabatic invariants may explain the features of ion spectral variations in outer boundary of the ring current observed by the INTERBALL-Tail probe during the quiet geomagnetic conditions. Collier [1999] also has focused on ion observations and found that velocity space diffusion is the important mechanism in a variety of different space plasma environments. Hence, studies on the spectral characteristics during the plasma injection may give an insight into the physical processes.

[4] In this study, the substorm dispersionless injection on 11 March 1998 seen at the geosynchronous orbit during a storm recovery phase is selected as a typical event to investigate the spectral characteristics of energetic electrons and ions. The spectra for electrons and ions have been fitted with the three-parameter kappa distribution during four different substorm phases (pregrowth phase, the growth phase, the expansion phase and the recovery phase) with the Levenberg-Marquardt and Universal Global Optimization methods. It is noted that the convection velocity has no impact on the derivatives of three parameters \( \alpha_0, \kappa, E_0 \). The evolution of the three parameters is discussed in detail and the correlation between the power law index \( \kappa \) and the characteristic energy \( E_0 \) is analyzed.

2. Data and Method

[5] The energetic electron and ion differential directional flux measurements made by the Synchronous Orbit Plasma Analyzer (SOPA) instruments [Belian et al., 1992] on the geosynchronous LANL satellite 1991–080 on 11 March 1998 are used. The 10s time resolution data are separated into 9 energy channels, ranging from 50 keV to 1.5 MeV, for electrons, and 12 energy channels ranging from 50 keV to 50 MeV, for ions. The SOPA instrument consists of three nearly identical silicon solid state detectors oriented with differing look directions. The detectors consist of a very thin front silicon detector and a thick back detector. The discrimination of species is made by measuring the total energy deposited in each detector and setting energy boundaries as a function of the two detectors. The P1 Channel (50–75 keV) often has contaminated by some electrons. The threshold in P1 is set to 42 keV which corresponds to incident proton energy of 50 keV, therefore about 8% of 42 keV electrons will be stopped in the front detector and be falsely identified as protons. The energies are logarithmically spaced so a power law will produce roughly even spacing between adjacent channels. Generally the P1 channel should not be used because the spacing between P1 and P2 is much larger than the one between the other channels but in the present case the noise level is low. The P6 Channel (400–670 keV) has a different problem. Usually \( >400 \) keV protons pass completely through the front detector and start to deposit energy in the back detector so starting with P6 requires finite energy in both detectors. However, if the low-energy electron \((<50 \text{ keV})\) deposits energy in the front detector and at the same time a high-energy electron \((>400 \text{ keV})\) deposits energy in the back detector, it will falsely be labeled as a proton in the P6 channel. This happens mainly in the P6 channel, so P6 channel has been discarded from our analysis.

[6] In this paper, the Levenberg-Marquardt and Universal Global Optimization (L-M and UGO) best fit methods, which can converge to the optimal solution for any random initial value, have been adopted to fit flux-energy curve. These are more efficient and effective than local optimization algorithms and overcome the difficulty of assuming the initial value.

3. Observations

[7] As shown in Figure 1, a magnetic storm occurred on 10 March 1998 which was driven by a 6 h interval of nearly persistent southward IMF magnetic field that reached \( \sim17 \) nT during the trailing half of a Corotation Interaction Region (CIR). The minimum SYM-H index is \( \sim19 \) nT. The interval studied in this paper is characterized by the gray shade in Figures 1a and 1b during the recovery phase of the magnetic storm. The satellite 1991–080 was located in magnetic local time from 21.4 to 23.6 on the night side during the interval as shown in Figure 2. A substorm event occurred in the interval where the AL index increased form 216 to 859 nT as shown in Figure 1c. The substorm expansion phase onset was identified at \( \sim22:57 \) UT by POLAR UVI images as shown in the Figure 3. There was a brightening from \( \sim21 \) to \( \sim3 \) MLT and \( \sim55^\circ \) to \( \sim65^\circ \) magnetic latitude which then extended to the range \( \sim4 \) MLT and \( \sim50^\circ \) to \( \sim70^\circ \) magnetic latitude at \( \sim23:00 \) UT. The dispersionless injection events between 2100 UT and 2316 UT on 11 March 1998 is shown in Figures 4a and 4b for electrons and ions respectively. Before injection the fluxes show a slight decrease starting at \( \sim22 \) UT; this corresponds to the growth phase of the substorm indicated by a horizontal green bar with a leftward and a rightward arrow in the figure. The electron fluxes at 22:55:16 UT suddenly enhance to about 100 times of the preinjection level in 5 minutes. This phase identifies with the substorm expansion phase indicated by a red bar with left-right arrows. Ion injection can also be clearly seen in Figure 4b. The flux enhancement ratio for electrons tends to decrease with increasing energy, while for ions it increases and remains elevated with increasing energy. The ion flux for 400–670 keV is higher than that of 250–400 keV during the whole process, which was contaminated by the electrons and hence will be not considered as mentioned in section 2. The four different phases (pregrowth phase, the growth phase, the substorm expansion phase and the recovery phase) are indicated in Figures 4a and 4b by four horizontal bars with different colors.

[8] Figures 4c and 4d show the resulting spectra on log-log plots. The four dash color lines represent the spectral distribution for electrons and ions at four representative times (21:29:57, 22:29:45, 22:58:15, and 23:09:22) during different substorm phases respectively. The four different curves are best fitted with the three-parameter kappa distribution function \( f \sim \alpha_0 \cdot E^{[1 + E/(\kappa E_0)]^-1} \) by Levenberg-Marquardt and Universal Global Optimization methods. The spectra before and during the growth phase are very similar and their changes can be described by a vertical shift.
Although \( E_0 \) and \( \kappa \) are independently fitted parameters, they are highly correlated and appear to be well described by a linear relationship with a positive intercept as \( \kappa(E_0) = \kappa_0 + \eta E_0 \). Table 2 summarizes the linear fit parameters and correlation coefficients for both electrons and ions.

### 4. Analysis

[11] The relationship between \( \kappa \) and \( E_0 \) observed by LANL can be explained by application of a diffusion model to the superthermal kappa distribution. The one dimensional steady kappa function is expressed as [Summers and Thorne, 1991]

\[
f(v) = \frac{n \Gamma (\kappa + 1)}{v \sqrt{\pi \kappa}^{3/2} \Gamma (\kappa - 1/2)} \left[ 1 + \frac{v^2}{\kappa v_c^2} \right]^{-\kappa},
\]

where \( v_c \) stands for the particle thermal speed. Meanwhile, the time-dependent terms particle distribution with initial kappa function form can be written as a series expansion,

\[
f(v, t) = f_0 + \sum_{j=1}^{\infty} f_j(t/v_c)^{\kappa_j} - \sum_{j=1}^{\infty} f_j(t/v_c)^{\kappa_j+1} + \sum_{j=1}^{\infty} f_j(t/v_c)^{\kappa_j+2} + \cdots
\]

where \( f(t = 0) = 0 \) for all \( j = 1, 2, \ldots, \infty \).

[12] It is assumed that expression (2) represents the evolution of particle distribution during injection which follows the diffusion equation in phase space:

\[
\frac{\partial f(v, t)}{\partial t} = D_0 \frac{\partial^2 f(v, t)}{\partial v^2},
\]

where \( D_0 \) is assumed to be a constant. The equation (3) can be inferred from the Fokker-Planck equation for the impulsive changes in the electric field over time scales much shorter than the gyroperiod [Newman and Newman, 1991]. This is very similar to the pulse electric field observed

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**Figure 1.** (a) The SYM-H index and (b) IMF Bz on the 11 March 1998 magnetic storm. The gray shadow at the recovery phase is the dispersionless substorm injection studied in this paper. (c and d) The SYM-H index and IMF Bz during the event interval. (e) The AE index during the event.

[9] The Kappa distribution function are applied to all the selected time intervals. Figure 5 illustrates the evolutions of the three parameters \( A_0, \kappa, E_0 \) with time. In the following parameter subscripts with letters \( e \) and \( i \) will denote electrons and ion respectively. During the first and the second phases, the mean value of \( \kappa_i \) is always greater than that of \( \kappa_e \), i.e., the most probable value of \( \kappa_e \) is between 2.5 and 3.0 and \( \kappa_i \) is between 3.5 and 4.5. The value of \( E_0 \) is roughly comparable to that of \( E_0 \), and they are both approximately \( \sim 1.5 \) keV. \( A_0 \) for both populations remains at about \( 10^8 \) in magnitude, while the dispersionless injection proceeds, \( E_0 \) and \( \kappa \) increase significantly. \( E_0 \) increased from 0.5 to 3 keV and \( E_0 \) from 1 to 15 keV; \( \kappa_e \) varied from 2.5 to 4.1 and \( \kappa_i \) from 3.0 to 6.0. On the other hand, \( A_0 \) increases from below \( 10^8 \) to above \( 10^9 \) for electrons, which is over 10 times larger than that before the injection whereas for electrons it decreases from \( 10^8 \) to \( 10^4 \), which is about \( 1/10000 \) of the level before the injection. The statistical errors of the three parameters during the four different phases are presented in Table 1.

[10] Figure 6 shows a plot of spectral power law index \( \kappa \) versus characteristic energy \( E_0 \) for the four different phases.
Figure 3. POLAR UVI images for the event interval.
Because the diffusion equation (3) yields during the substorm injection. Applying equation (2) to the diffusion equation (3) yields

\[
\sum_{j=1}^{\infty} \frac{\ddot{f}_j(t)}{\nu^{2k_{\nu}+j}} + \sum_{j=1}^{\infty} \frac{\dot{f}_j(t)}{\nu^{2k_{\nu}+j+1}} = D_0 \left\{ \frac{f_0[2k_{\nu}(2k_{\nu}+1)]}{\nu^{2k_{\nu}+2}} + \sum_{j=1}^{\infty} \frac{f_0[2k_{\nu}+j](2k_{\nu}+j+1)}{\nu^{2k_{\nu}+j+2}} - \frac{f_0[2k_{\nu}+2](2k_{\nu}+3)}{\nu^{2k_{\nu}+4}} - \sum_{j=1}^{\infty} \frac{f_0[2k_{\nu}+j+2](2k_{\nu}+j+3)}{\nu^{2k_{\nu}+j+4}} \right\}.
\]

(4)

Because \(f_0\), \(f_0'\) and \(f_0''\) are independent of time, it is reasonable to assume that \(\dot{f}_0 = 0\), \(\dot{f}_0' = 0\) and \(\dot{f}_0'' = 0\). Comparing terms with identical powers of \(\nu\) gives

\[
\begin{align*}
\dot{f}_0(t) &= 0 \Rightarrow f_i(t) = \text{const} \Rightarrow \dot{f}_0(t) = 0 \\
\dot{f}_0'(t) &= 2\nu f_0(2k_{\nu}+1)f_0D_0 \Rightarrow f_i(t) = 2\nu f_0(2k_{\nu}+1)f_0D_0t \\
\dot{f}_0''(t) &= f_0(t)(2k_{\nu}+1)(2k_{\nu}+2)D_0 = 0 \Rightarrow f_i(t) = 0, \quad f_i'(t) = 0 \\
\end{align*}
\]

(5)

Defining the slope of \(f(\nu, t)\) on a logarithmic scale,

\[
\kappa(\nu, t) = -\frac{d(\ln f)}{d(\ln \nu)} = -\frac{\nu}{2} \frac{df}{d\nu}.
\]

(6)

Inserting equations (2) and (5) into equation (6) and neglecting the terms of \(O(\nu^{-4})\) and higher-order terms, and using Newman and Newman's [1991, equations (15) and (23)], that \(v_0^2 = v_0^2 + 4D_0t\), equation (6) can be written as

\[
\kappa(\nu, t) = \kappa_0' + \left( -\frac{\kappa_0'(2k_{\nu}+1)}{2} + f_0 \frac{v_0^2}{4f_0'} \right) \frac{v_0^2}{v^2} + \frac{1}{2} \frac{\kappa_0'(2k_{\nu}+1)}{4f_0'} \frac{v_0^2}{v^2} 
\]

(7)

Note that \(E_0' =mv_0^2/2\) is the initial thermal energy, \(E_0 =mv_0^2/2\) is the characteristic energy, and \(E =mv^2/2\), so that

\[
\kappa(E_0) = \kappa_0 + \eta E_0.
\]

(8)
Figure 5. Evolutions of the three parameters of the best fit kappa distribution function for (a–c) electrons and (e–g) ions respectively from LANL 1991–080 for the 2100–2400 UT period on 11 March 1998. (d and h) The density inferred from the three parameters.
The Average, Median, and the Standard Errors of Spectral Parameters During the Four Different Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Average</th>
<th>Median</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-growth</td>
<td>$A_{0}$</td>
<td>$E_{0}$</td>
<td>$\kappa$</td>
</tr>
<tr>
<td>Ions</td>
<td>$(8.29 \times 10^{17})$</td>
<td>$(8.04 \times 10^{17})$</td>
<td>$(0.92 \times 10^{17})$</td>
</tr>
<tr>
<td>Electrons</td>
<td>$(1.74 \pm 0.09)$</td>
<td>$(1.71 \pm 0.09)$</td>
<td>$(0.93 \pm 0.86)$</td>
</tr>
<tr>
<td>Growth</td>
<td>$A_{0}$</td>
<td>$E_{0}$</td>
<td>$\kappa$</td>
</tr>
<tr>
<td>Ions</td>
<td>$(5.88 \times 10^{17})$</td>
<td>$(5.68 \times 10^{17})$</td>
<td>$(0.82 \times 10^{17})$</td>
</tr>
<tr>
<td>Electrons</td>
<td>$(1.45 \pm 0.37)$</td>
<td>$(1.38 \pm 0.13)$</td>
<td>$(0.87 \pm 0.86)$</td>
</tr>
<tr>
<td>Expansion</td>
<td>$A_{0}$</td>
<td>$E_{0}$</td>
<td>$\kappa$</td>
</tr>
<tr>
<td>Ions</td>
<td>$(1.24 \times 10^{17})$</td>
<td>$(1.10 \times 10^{17})$</td>
<td>$(0.82 \times 10^{17})$</td>
</tr>
<tr>
<td>Electrons</td>
<td>$(4.21 \pm 3.85)$</td>
<td>$(3.24 \pm 3.15)$</td>
<td>$(0.87 \pm 0.86)$</td>
</tr>
<tr>
<td>Recovery</td>
<td>$A_{0}$</td>
<td>$E_{0}$</td>
<td>$\kappa$</td>
</tr>
<tr>
<td>Ions</td>
<td>$(9.18 \times 10^{17})$</td>
<td>$(8.79 \times 10^{17})$</td>
<td>$(0.82 \times 10^{17})$</td>
</tr>
<tr>
<td>Electrons</td>
<td>$(2.19 \pm 0.19)$</td>
<td>$(2.09 \pm 0.19)$</td>
<td>$(0.93 \pm 0.86)$</td>
</tr>
</tbody>
</table>

Here

$$\kappa_0 = \kappa_0 + \left[ \frac{k_0}{2} + \frac{\kappa_0}{2} \right] \left[ \frac{E_0}{E} \right]$$

$$\eta = \left[ \frac{\kappa_0}{2} + \frac{\kappa_0}{2} \right] \left[ \frac{E_0}{E} \right] \frac{1}{E}.$$ This result implies that both $\kappa_0$ and $\eta$ are independent of $E_0$.

Equation (8) can explain the relationship between the power law index $\kappa$ and the characteristic energy $E_0$ observed by LANL satellite, since $\eta$ represents the slope of $\kappa$ versus characteristic energy $E_0$. Since the distribution will become more Maxwellian as $D_\alpha$ increases relative to the initial $E_0$, it can be seen [from Newman and Newman, 1991, equations (15), (23), and (8)] that we have inferred from LANL measurement that the best fitting of $\kappa$ and $E_0$ in which $\kappa$ increases with time, through application of the diffusion model to the superthermal kappa distribution. Therefore diffusion of particles in the velocity space plays the dominant role in this substorm injection event. It is worth noting that the distribution which evolves from an initial kappa function through velocity space diffusion can maintain its kappa form.

5. Discussions and Conclusions

The statistical errors of particle flux measurements can lead to real errors in the three parameters of the kappa distribution function. The average, median, and statistical errors of the three parameters during the four different phases have been calculated. During the pre-growth and growth phases the errors of $E_0$ and $\kappa$ are relatively lower than those of the later two phases. During the expansion phase the errors are found to exceed 40% for electrons and more than 80% for ions, implying the severe variations of the three parameters at substorm injection.

The electron $\kappa$ index at geosynchronous orbit is smaller than that in the plasma sheet at geocentric radial distance $R > 12R_E$, where $\kappa$ is typically in the range 4.0–8.0 [Christon et al., 1988]. This is in better agreement with the geosynchronous observations and consistent with the lower kappa value commonly used in MHD simulations [Birn et al., 1998]. The factor $A_0$ is related to the number density by

$$A_0 \sim n_0 \left[ \frac{\kappa E_0}{\kappa_0 E_0} \right]^{1/2},$$

where $E_0$ is the characteristic energy, and the number density variations have been shown in the bottom of Figure 5. Although the factors $A_0$ for electrons and ions vary oppositely, the electron density increases by two orders after substorm injection and the proton density increases slightly. Usually, the acceleration (depending on how soft the energy spectrum is) and the increase density of energetic particles number density at the observational point result in flux enhancement. The sudden increase in the electron density means that electrons may be injected Earthward from the magnetotail by an inductive electric field and a dipolarization of the magnetic field [Li et al., 1998; Zaharia et al., 2004]. The slight rise in the ion density after injection could be explained by the local acceleration. Birn et al. [2000] found that electrons are mainly accelerated by both betatron and Fermi acceleration mechanisms, while ions behave nonadiabatically and get accelerated by the cross-tail electric field based on test particle orbit computations. Lee et al. [2004] reported that the average flux enhancement of ion injections tends to be bigger at higher-energy channels than at lower-energy channels,
whereas electron injections exhibit the opposite tendency as can be seen in the energy-spectral dependence of flux enhancements. They argued that different spatial distributions of the source populations can be a possible reason responsible for the difference in the flux enhancement between protons and electrons. In this paper, the analysis implies that the different diffusion processes in velocity space and common/mutual electric acceleration can explain why the flux enhancement ratio before and after injection of electrons is rather different from that of ions.

Figures 5b and 5f have been improved the equation \( v^2_c = v^2_{0c} + 4D_0 t \) and that it is quite believable to assume \( D_0 \) to be a constant. Based on the expressions \( k_0 \) and \( h \), it can be inferred that \( k_0 = h v^2_{0c} = k'_0 \), where \( v_{0c} \) and \( k'_0 \) are the initial core thermal speed and the initial power law index of the kappa distribution. It is remarkable that if \( k_0 \) increases then \( h \) decreases and they always vary with an opposite trend. As shown in Table 2 and Figure 7 during the four different phases, for the electrons \( k_0 \) decreasing accompanies increasing \( h \), while for ions \( k_0 \) increasing accompanies decreasing \( h \), which also indicates that the electron injection and the ion injection are controlled by different mechanisms. \( k \) is a parameter that can demonstrate physically the degree how a distribution resembles the Maxwel- lian distribution. The ions distribution with larger \( k \) always becomes a more Maxwellian-like distribution than that of the electrons during all the four phases.

Table 2. The Parameters and the Correlation Coefficients Between the Characteristic Energy and the Power Law Index Given by the Best Fit Function \( \kappa(E_0) = k_0 + \eta E_0 \) for the Four Different Phases

<table>
<thead>
<tr>
<th>Event Phases</th>
<th>( k_0 )</th>
<th>( n_0 )</th>
<th>( \eta_e )</th>
<th>( \eta_i )</th>
<th>( \chi_e )</th>
<th>( \chi_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pregrowth phase</td>
<td>2.626</td>
<td>2.157</td>
<td>0.071</td>
<td>1.024</td>
<td>0.928</td>
<td>0.574</td>
</tr>
<tr>
<td>Growth phase</td>
<td>2.303</td>
<td>2.19</td>
<td>0.325</td>
<td>1.153</td>
<td>0.860</td>
<td>0.669</td>
</tr>
<tr>
<td>Expansion phase</td>
<td>1.870</td>
<td>3.73</td>
<td>0.875</td>
<td>0.124</td>
<td>0.960</td>
<td>0.874</td>
</tr>
<tr>
<td>Recovery phase</td>
<td>2.471</td>
<td>2.853</td>
<td>0.456</td>
<td>0.436</td>
<td>0.900</td>
<td>0.692</td>
</tr>
</tbody>
</table>

Figure 6. Relationship between spectral power law index, \( \kappa \), and the characteristic energy, \( E_0 \), at four different phases for (left) electrons and (right) ions. The four color symbols are the observed results and the four color curves represent the best fitting results.

[16] In fact, the linear trends in kappa and \( E_0 \) observed in this event are quite general. Another substorm dispersionless injection event between 16:30 UT and 18:30 UT on 18 February 1998 has also been examined with the data from satellite 1994 – 084. The evolutions of the three parameters are similar to the event on 11 March 1998. The factor \( A_0 \) also shows the opposite trend for electron and ions. The number density for both species increases after the substorm injection. The electron density increases much more than that of ions. The same analysis as done on the 11 March 1998 event was carried out with the data obtained from LANL 97A which was located at dawn side during the injection. Unfortunately, the electron flux may have some contamination so only the ions data have been fitted. It is found that the ion distribution also shows a linear trend.

[17] In summary, the dispersionless substorm injection seen at geosynchronous orbit on 11 March 1998 during the

Figure 7. The variation of \( k_0 \) and \( \eta \) during the four phases. Superscript e represents electrons and i denoted for ion respectively.
storm recovery phase has been selected as a typical event for investigation of the spectral characteristics of energetic ions and electrons during injections. The three-parameter kappa distribution functions is best fitted to the electron and ion differential fluxes during the four different phases (pregrowth phase, during the growth phase, at the substorm expansion phase and the recovery phase). The main results are as the follows: (1) The distribution evolved from an initial kappa function through velocity space diffusion and maintain its kappa form, with the power law index and characteristics energy being different in each phase. (2) The factor $A_0$, related to the number density, varies with opposite trends for the ions and electrons. The characteristic energy $E_0$ and the power law index $\kappa$ both increase significantly with injection progression. (3) The approximately linear relationship between $\kappa$ and $E_0$ was shown to be held during the four different phases. Application of initial kappa distribution to the velocity space diffusion can also testify the linear relation. (4) These opposite variation trends of the number density, $E_0$ and $\kappa$ for ions and electrons indicate that electrons and ions injections have different acceleration mechanisms. (5) The velocity space diffusion processes can explain why the flux enhancement ratio before and after injection of electrons is rather different from that of ions. This implies that not only the common electric field acceleration, but also velocity space diffusion plays an important role in the particle injection.

References


