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Electron acceleration in the Van Allen radiation belts by fast magnetosonic waves

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Local acceleration is required to explain electron flux increases in the outer Van Allen radiation belt during magnetic storms. Here we show that fast magnetosonic waves, detected by Cluster 3, can accelerate electrons between $\sim$ 10 keV and a few MeV inside the outer radiation belt. Acceleration occurs via electron Landau resonance, and not Doppler shifted cyclotron resonance, due to wave propagation almost perpendicular to the ambient magnetic field. Using quasi-linear theory, pitch angle and energy diffusion rates are comparable to those for whistler mode chorus, suggesting that these waves are very important for local electron acceleration. Since pitch angle diffusion does not extend into the loss cone, these waves, on their own, are not important for loss to the atmosphere. We suggest that magnetosonic waves, which are generated by unstable proton ring distributions, are an important energy transfer process from the ring current to the Van Allen radiation belts.

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1. Introduction

The relativistic electron flux in Earth's outer radiation belt varies by over five orders of magnitude [*Baker and Kanekal*, 2007] and is responsible for certain types of satellite malfunctions [*Wrenn et al.*, 2002]. Flux variations are due to a combination of electron acceleration, transport, and loss processes acting within the magnetosphere [*Reeves et al.*, 2003; *Li et al.*, 1997], indicating that the magnetosphere is a gigantic particle accelerator. For many years inward radial diffusion from a source beyond geosynchronous orbit ($L = 6.6$) has been considered the dominant mechanism for transport and acceleration [*Schulz and Lanzerotti*, 1974], and is enhanced by ULF waves [*Elkington et al.*, 1999], but recent observations show that the electron phase space density can peak near $L = 4.5$ [*Green and Kivelson*, 2004; *Iles et al.*, 2006] suggesting that a local acceleration process is required. Acceleration by whistler mode chorus waves is an important mechanism for local acceleration [*Horne and Thorne*, 1998; *Summers et al.*, 1998, 2002; *Meredith et al.*, 2002; *Horne et al.*, 2003, 2005a], and was shown to be particularly effective in accelerating electrons during the 2003 Halloween magnetic storm [*Horne et al.*, 2005b] and in the slot region during other storms [*Thorne et al.*, 2007]. Here we show that another type of wave, known as fast magnetosonic waves, can also be very effective in accelerating electrons up to relativistic energies in the outer radiation belt, and must be considered as an additional local acceleration mechanism.

2. Wave observations

Figure 1 shows fast magnetosonic waves detected by the STAFF instrument [*Cornilleau-Wehrlin et al.*, 2003] on CLUSTER 3 as it crossed the magnetic equator on 25 Nov 2002.

The event occurred during an unusually long storm recovery phase when the ring current was enhanced for a 4-5 day period ($D_{st} \sim -40nT$), and when the > 2 MeV electron flux measured by GOES 10 (not shown) was a factor of 10 higher than the pre-storm level before 21 Nov. The waves can be identified by the intense emissions between 20 and 60 Hz, below the lower hybrid resonance frequency f_{LHR} (solid line) but above the local proton gyrofrequency f_{cH}, which is approximately 5.1 Hz at the equator. The waves are confined to a magnetic latitude of $\lambda_m \approx \pm 3^o$, and are far more intense than chorus for this event, which is the band of emissions above f_{LHR} rising in frequency towards the equator. The waves were detected in both the electric and magnetic antennas indicating that they are electromagnetic and have a high degree of elliptical polarization (with ellipticity ≈ 0) from which the calculated direction of the $\mathbf{k}$ vector is approximately $\psi = 89^o$ with respect to the ambient magnetic field direction $\mathbf{B_o}$. The frequency range and degree of ellipticity indicate that the waves propagate across the magnetic field with the wave electric field in the plane almost perpendicular to $\mathbf{B_o}$ and $\mathbf{k}$ with the wave magnetic field along $\mathbf{B_o}$. These waves are known as fast magnetosonic waves or equatorial noise. Earlier observations reported waves between $2 \leq L \leq 7$, [e.g., *Gurnett*, 1976; *Perraut et al.*, 1982; *Laakso et al.*, 1990] within 10^o of the magnetic equator [*Santolík et al.*, 2004]. More recent studies show that the intensity of the waves peaks within $\lambda_m \sim 2^o - 3^o$ [*Santolík et al.*, 2002; *Němec et al.*, 2005]. Magnetosonic waves are generated by a proton ring distribution at frequencies close to the harmonics of the proton gyrofrequency [*Boardsen et al.*, 1992, *Horne et al.*, 2000] and can propagate both inside and outside the plasmapause [*Kasahara et al.*, 1994; *Horne et al.*, 2000].

3. Resonant wave-particle interactions

Magnetosonic waves can interact strongly with electrons and ions via Doppler shifted cyclotron resonance, given by

$$\omega - n\Omega_\sigma/\gamma - k_\parallel v_\parallel = 0 \tag{1}$$

where ω is the angular wave frequency, Ω_σ is the cyclotron frequency for a particle species σ, n is the harmonic number, γ is the relativistic mass correction factor and $v_\parallel$ is the electron velocity component parallel to the background magnetic field direction $\mathbf{B_o}$. Solving this equation together with the dispersion relation for whistler mode propagation at large angles we can obtain the electron resonant energies and pitch angles. For the band of waves observed by CLUSTER 3 between $0.0026 \leq \omega/|\Omega_e| \leq 0.0044$, with $\omega_{pe}/|\Omega_e| = 3$ and assuming $\psi = 89^o$, all cyclotron resonances occur at energies well above 3 MeV (Figure 2) and are therefore unlikely to play a significant role in electron scattering. However, Landau ($n = 0$) resonance (central vertical dashed line for $\psi = 89^o$) is possible over a wide range of energies from below 100 keV up to the speed of light and occurs at larger pitch angles with increasing energy. Note that Landau resonance extends over a range of $v_\parallel/c$ when a band of waves with a spread of wave normal angles is taken into account, as described below.

For a broad band of waves, such as those shown in Figure 1, it is more appropriate to discuss electron scattering as a diffusion process in pitch angle and energy. To determine the efficiency of the interaction it is necessary to calculate the diffusion coefficients and determine the shape of the pitch angle distribution. The diffusion coefficients depend on the distribution of wave power in frequency and wave normal angle and are given by

Glauert and Horne [2005]. Figure 3a shows the magnetic field wave intensity obtained from a least squares fit to the 1s CLUSTER 3 data (black) and the 45s averaged data (red). The wave intensity is high over a three minute interval as the satellite crosses the magnetic equator. A least squares fit to a Gaussian distribution for the data averaged between 16:29:36 and 16:32:36 UT gave a peak frequency at $\omega_m/|\Omega_e| = 3.49 \times 10^{-3}$, a width $\delta\omega/|\Omega_e| = 8.86 \times 10^{-4}$ and a wave amplitude $B_w = 218$ pT (Fig. 3b). The angular distribution was also assumed to be Gaussian in $X = \tan\psi$ peaked in a direction $X_m = \tan 89^o$ with a width $X_w = \tan 86^o$. Interactions between waves and electrons at higher latitudes were taken into account by bounce averaging the diffusion rates assuming the wave power remains constant for $\lambda_m \leq \pm 3^o$, and zero at higher latitudes, using a constant plasma density and dipole magnetic field. The bounce averaged pitch angle $< D_{\alpha\alpha} > /p^2$ and energy $< D_{EE} > /E^2$ diffusion coefficients, in units of s^{-1}, are shown in Figure 4 for $L = 4.5$.

Scattering rates are most effective at large pitch angles $> 50^o$ with energy diffusion timescales of the order of a day between 0.3 and 1 MeV, and a few days at 0.1 and 3 MeV. Since pitch-angle scattering does not extend into the loss cone, which is approximately 4.5^o at $L = 4.5$, magnetosonic waves will not cause electron precipitation loss into the atmosphere. Instead, the waves cause electron stochastic acceleration from energies of ~ 0.1 to a few MeV. The energy difusion rates are comparable to those for whistler mode chorus during magnetic storm times [*Horne et al.*, 2003; 2005a], with timescales comparable to that for electron acceleration during the recovery phase of magnetic storms, which is typically 1-2 days [*Baker et al.*, 1994]. Note that the energy diffusion rates maximise between

$50^o - 80^o$, so that magnetosonic waves would tend to produce a butterfly type pitch angle distribution.

Since magnetosonic waves are also observed inside the high density plasmasphere, Figure 5 shows the diffusion rates at $L = 4.5$ for $f_{pe}/f_{ce} = 10$. Increasing the plasma frequency reduces the parallel phase velocity of the waves so that resonance with the same energy electrons occurs at larger pitch angles (Figure 2). Note also that energy diffusion is increased at lower energies as a result of the change in phase velocity, so that substantial acceleration is now possible from energies near 30 keV. However, energy diffusion rates at 1 MeV are substantially smaller inside the plasmasphere.

4. Discussion and Conclusions

Ion ring distributions form in the ring current during magnetic storms as a result of losses due to slow ion drift [*Lennartsson et al.*, 1981; *Fok et al.*, 1995]. Since magnetosonic waves are generated by ion ring distributions and accelerate electrons, we suggest that they contributed to the elevated electron flux observed during the event on 25 Nov 2002, and could be an important energy transfer process from the ring current to the Van Allen radiation belts. However, since acceleration may occur simultaneously with loss by other wave modes at other MLT regions, there may not be a simple relationship between the strength of the ring current and the radiation belt flux.

A full assessment of the importance of these waves for electron acceleration requires detailed analysis of the occurrence rate of magnetosonic wave power and it's variation with L, MLT, λ_m, and magnetic activity. To assess how important they could be, we note that magnetosonic waves between f_{cH} and f_{LHR} have the most intense magnetic field fluctuations of all the natural emissions in this frequency range and an occurrence rate of 60% between 3.9 and $5R_e$ measured by CLUSTER over all MLT [*Santolík et al.*, 2004]. Using this to assume that electrons interact with waves for 60% of the drift orbit, the bounce and drift averaged energy diffusion rates for magnetosonic waves are comparable to those for whistler mode chorus [*Horne et al.*, 2005a]. Since chorus waves are very effective in producing MeV electrons [*Varotsou et al.*, 2005], we suggest that electron acceleration by magnetosonic waves could be as important as acceleration by chorus.

Magnetosonic waves will accelerate a seed population of $\geq$ 10 keV electrons. Thus some source of electron injection, such as substorms, is still required to transport $\sim$ 10 keV electrons into $L \sim 4$. Acceleration of the low energy component is most effective inside the high density plasmapause, but higher energies will be achieved outside. Since magnetosonic waves do not scatter into the loss cone, the need for a continuous supply of low energy electrons is not as stringent as it is for acceleration by chorus.

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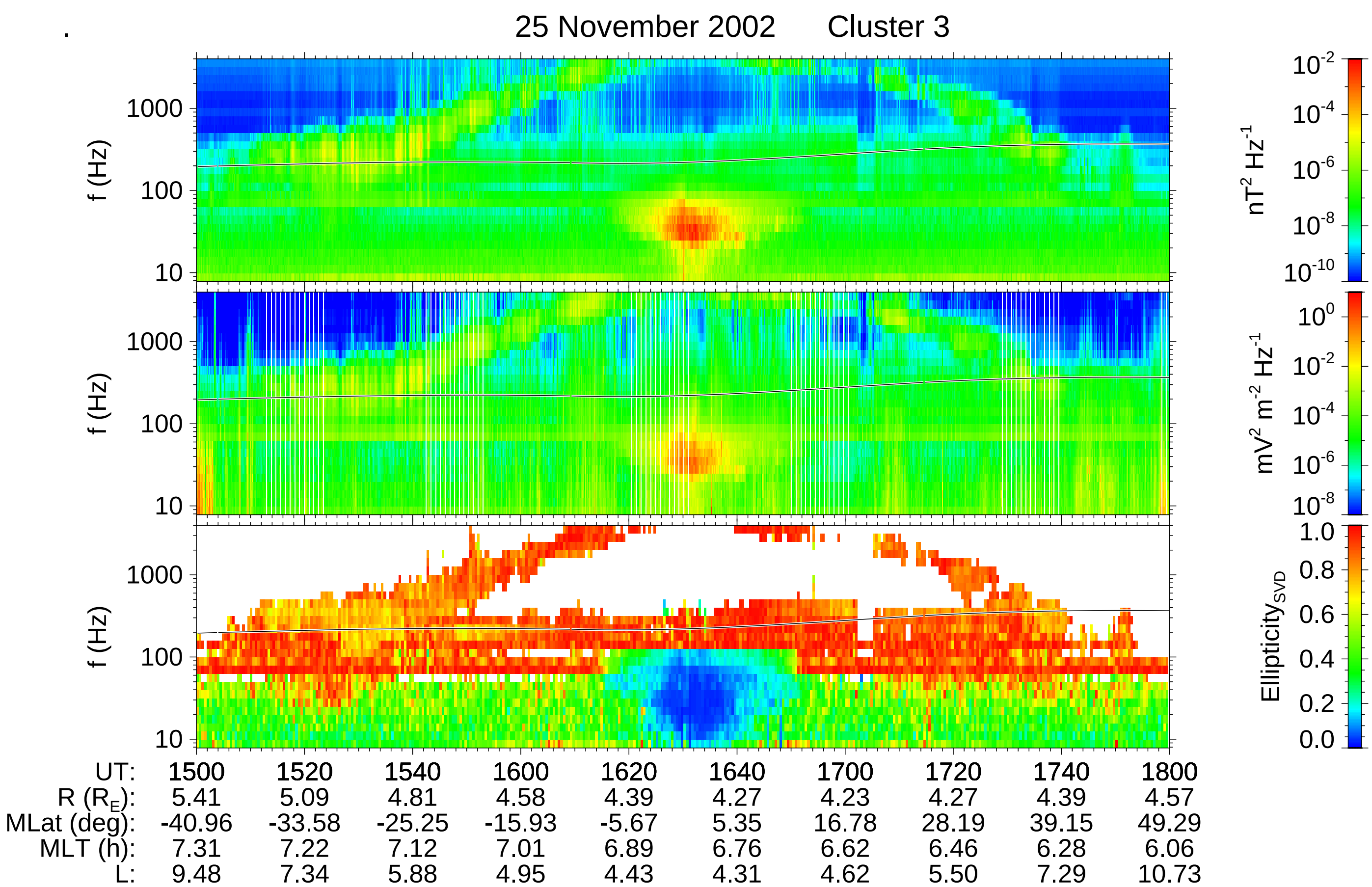
Figure 1. Magnetosonic waves observed by CLUSTER 3 on 25 November 2002. (Top) magnetic and (middle) electric field power spectral density. (Bottom) wave ellipticity.

Figure 2. Resonant ellipse for magnetosonic waves interacting with electrons, showing (dashed) Landau $n = 0$ and (solid) $n = 1$ Doppler shifted cyclotron resonances, (dotted) circles of constant electron energy, and (dot-dash) loss cone. The central dashed line is for Landau resonance at $X_m = \tan 89^o$, the lines either side are for propagation with a range of wave-normal angles $X_m \pm X_w$ (see text).

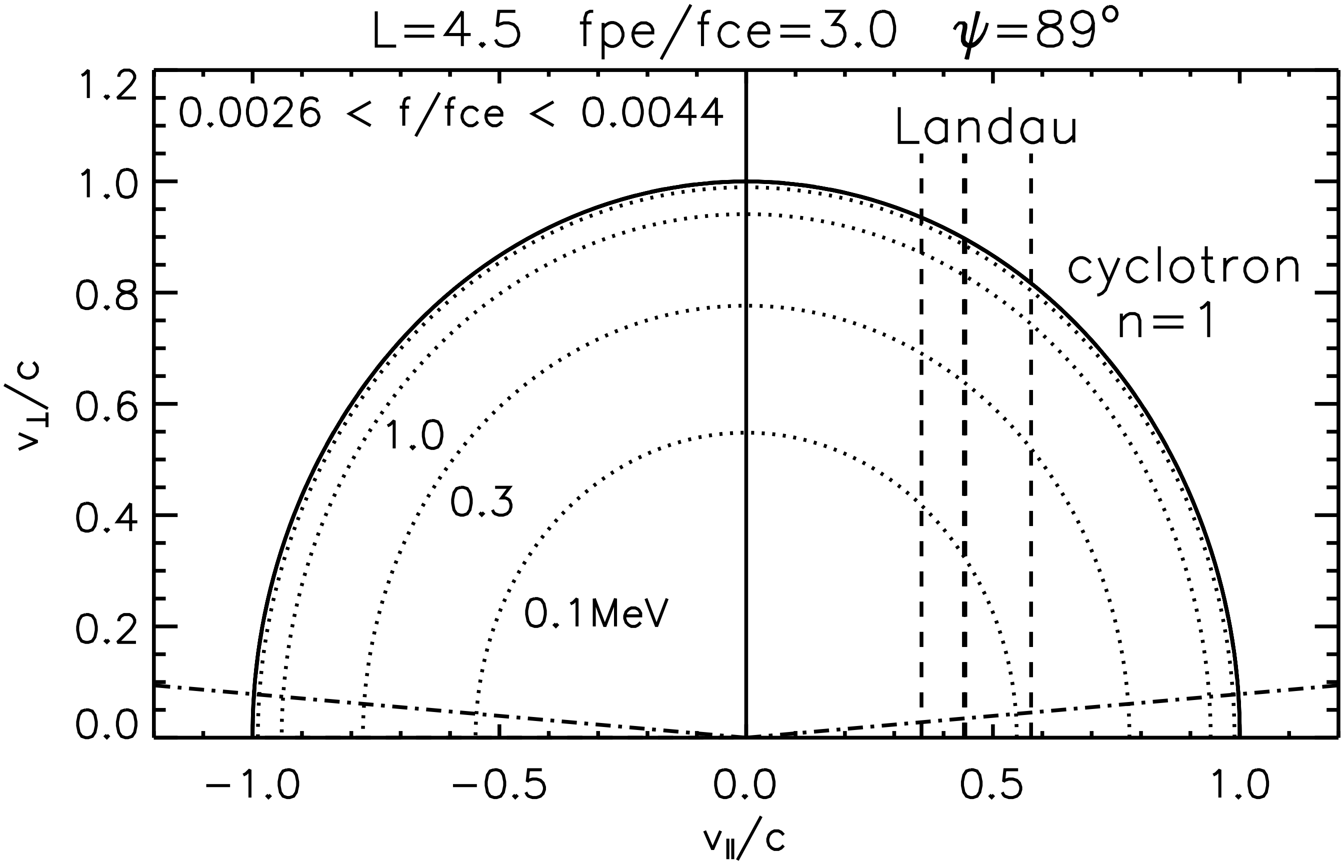
Figure 3. (a) magnetic field wave intensity for magnetosonic waves as CLUSTER 3 crossed the magnetic equator. (b) Wave spectral intensity and model fit to a Gaussian distribution.

Figure 4. (a) Bounce averaged electron pitch angle and (b) energy diffusion coefficients at $L = 4.5$ and $f_{pe}/f_{ce} = 3$ for selected energies.

Figure 5. As Figure 4 but for $f_{pe}/f_{ce} = 10$.

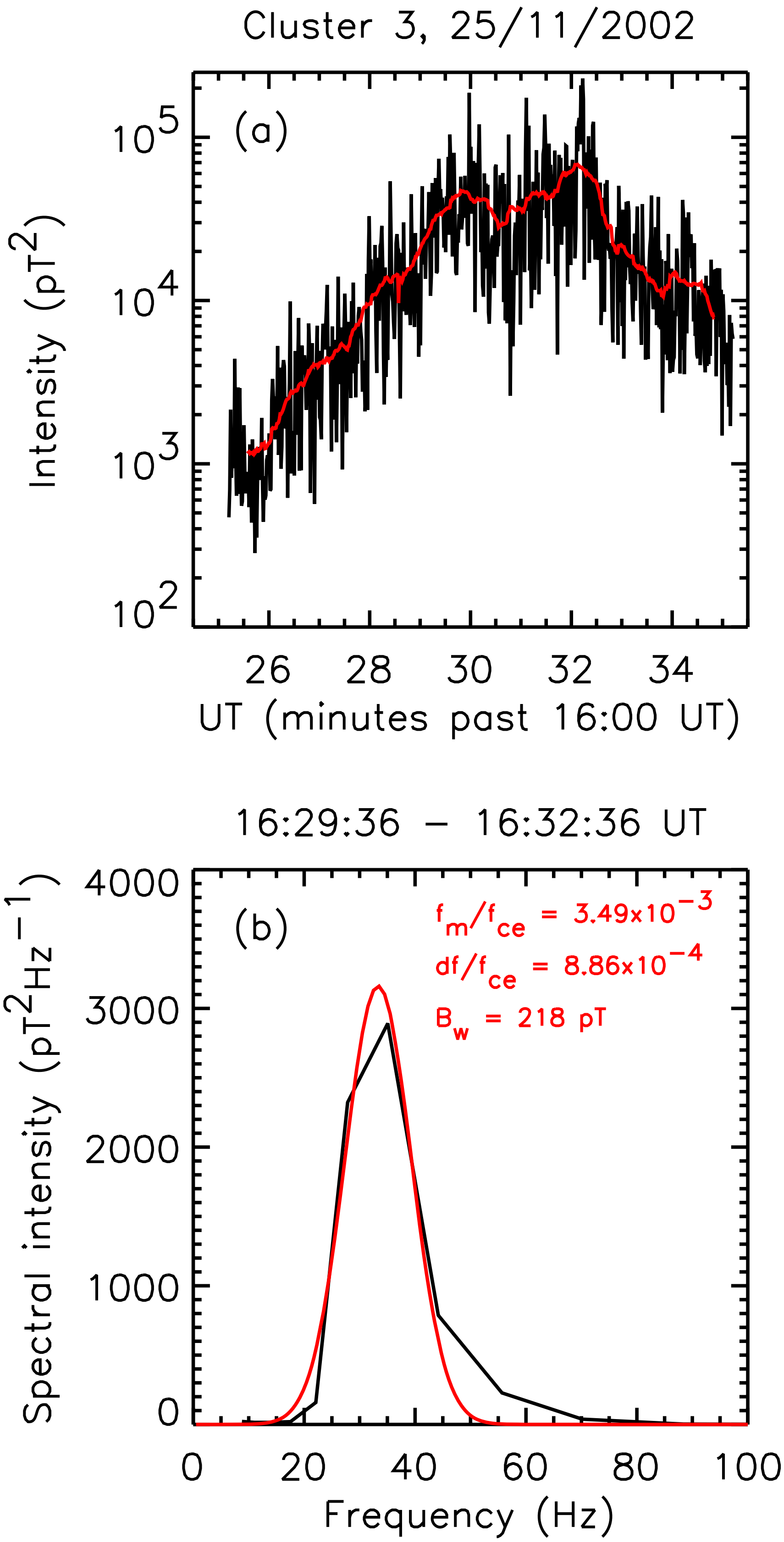


25 November 2002 Cluster 3
f (Hz)
1000
100
10
nT² Hz⁻¹
mV² m⁻² Hz⁻¹
Ellipticity_SVD
1.0
0.8
0.6
0.4
0.2
0.0
UT: 1500 1520 1540 1600 1620 1640 1700 1720 1740 1800
R (R_E): 5.41 5.09 4.81 4.58 4.39 4.27 4.23 4.27 4.39 4.57
MLat (deg): -40.96 -33.58 -25.25 -15.93 -5.67 5.35 16.78 28.19 39.15 49.29
MLT (h): 7.31 7.22 7.12 7.01 6.89 6.76 6.62 6.46 6.28 6.06
L: 9.48 7.34 5.88 4.95 4.43 4.31 4.62 5.50 7.29 10.73



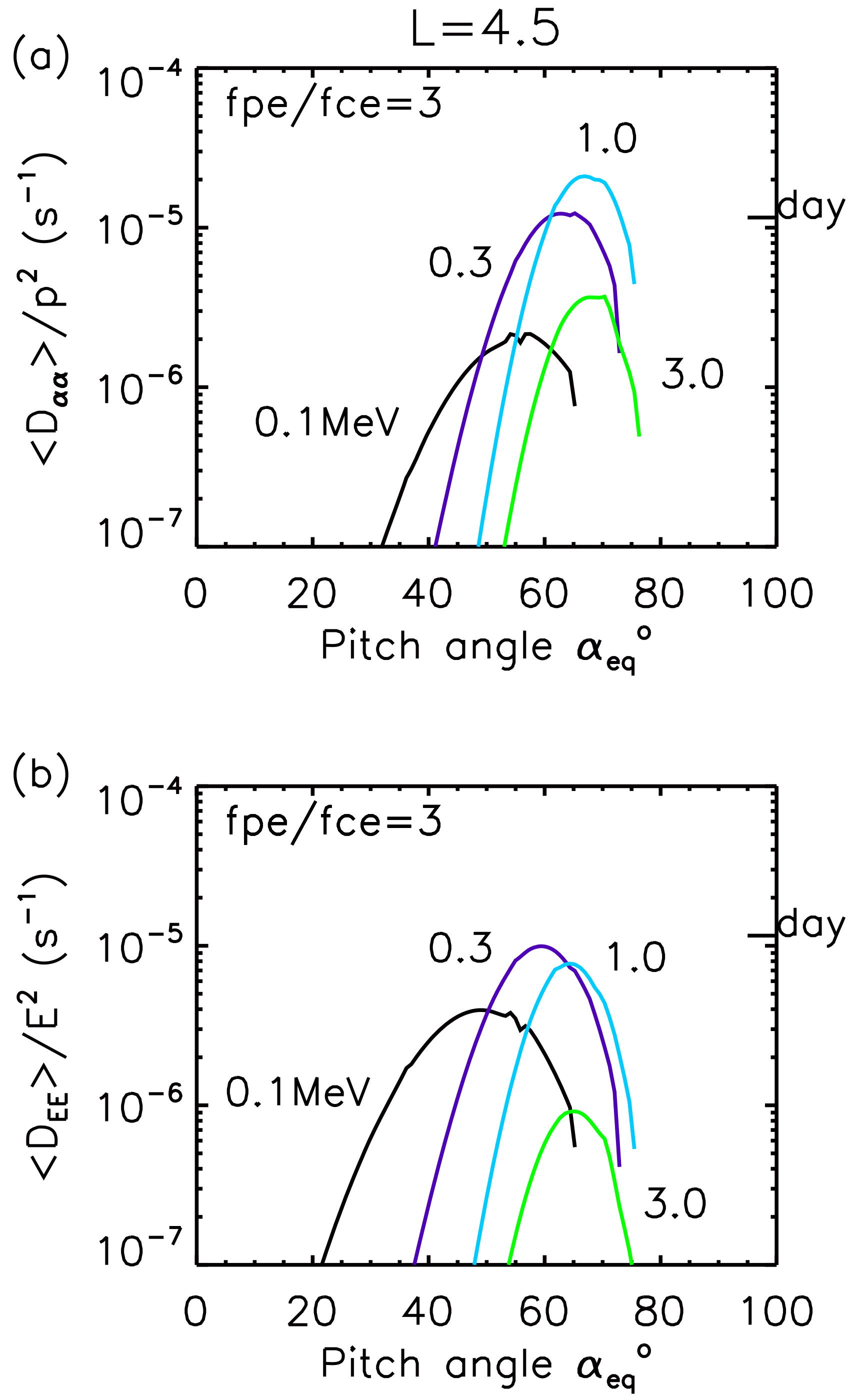
L=4.5 fpe/fce=3.0 ψ=89°
0.0026 < f/fce < 0.0044
Landau
cyclotron
n=1
1.0
0.3
0.1MeV
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0
v⊥/c
v∥/c

Figure_2



Cluster 3, 25/11/2002
(a)
Intensity (pT^2)
10^5
10^4
10^3
10^2
26
28
30
32
34
UT (minutes past 16:00 UT)
16:29:36 – 16:32:36 UT
(b)
Spectral intensity (pT^{2}Hz^{-1})
f_m/f_{ce} = 3.49x10^{-3}
df/f_{ce} = 8.86x10^{-4}
B_w = 218 pT
4000
3000
2000
1000
0
0
20
40
60
80
100
Frequency (Hz)

Figure 3



L=4.5
(a)
fpe/fce=3
1.0
0.3
3.0
0.1MeV
day
$\langle D_{\alpha\alpha}\rangle/p^2$ (s^{-1})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
20
40
60
80
100
Pitch angle α_{eq}°
(b)
fpe/fce=3
0.3
1.0
0.1MeV
3.0
day
$\langle D_{EE}\rangle/E^2$ (s^{-1})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
20
40
60
80
100
Pitch angle α_{eq}°

Figure_4

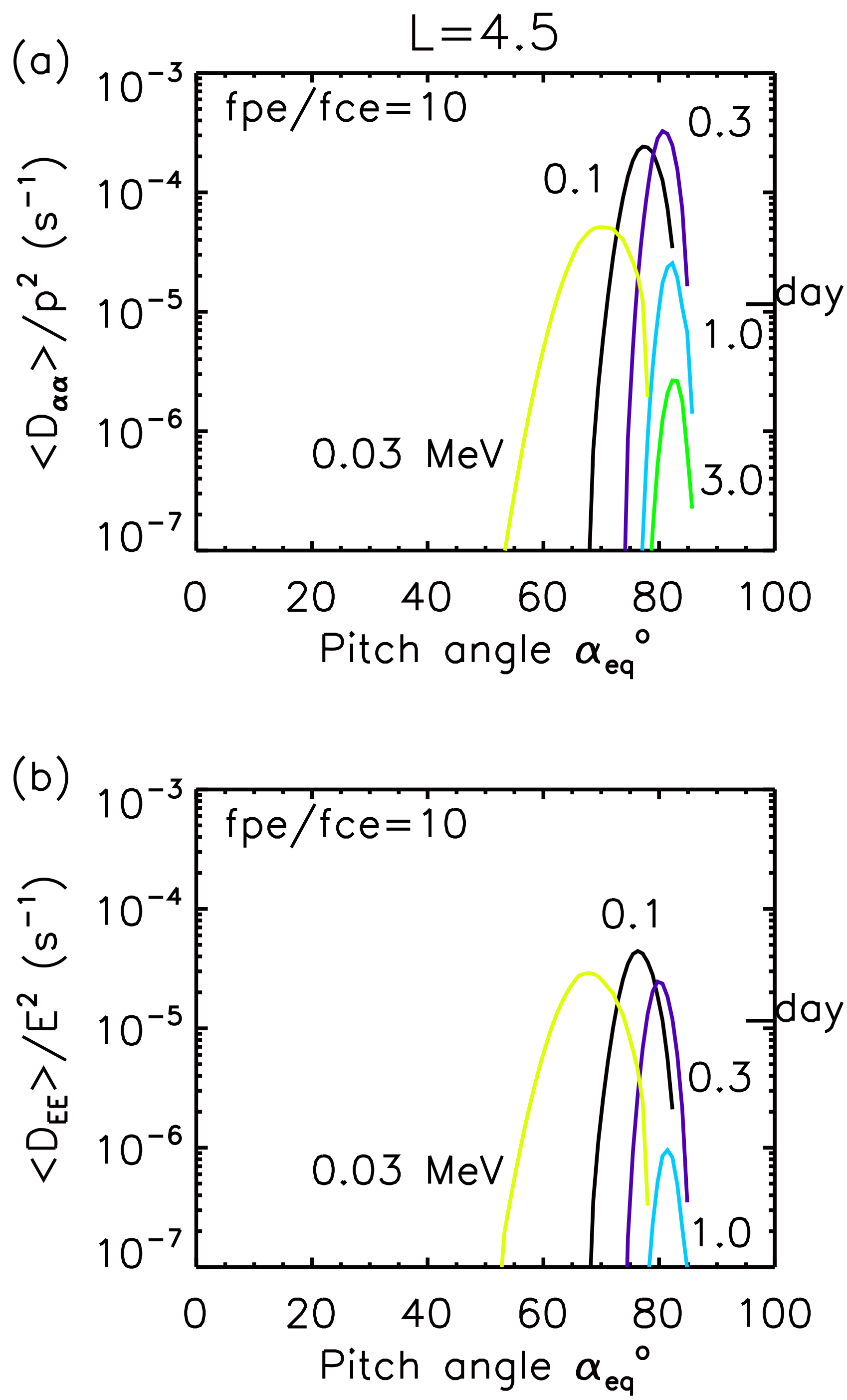

L=4.5
(a)
fpe/fce=10
0.3
0.1
day
1.0
0.03 MeV
3.0
$<D_{\alpha\alpha}>/p^2$ (s^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
20
40
60
80
100
Pitch angle α_{eq}°
(b)
fpe/fce=10
0.1
day
0.3
0.03 MeV
1.0
$<D_{EE}>/E^2$ (s^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
20
40
60
80
100
Pitch angle α_{eq}°

Figure_5