Effects of thunderstc
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away electrons

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INTRODUCTION

In the previous works [*Lehtinen et al.*, 1997; 1999], we studied the energetic runaway electrons above thunderstorms, avalanching upward due to quasielectrostatic field following a positive cloud-to-ground discharge.

What happens to runaway electrons originating above thunderstorms after they run away? They can:

- interact with plasma waves in the ionosphere and magnetosphere
- precipitate at the geomagnetically conjugate point
- backscatter at the conjugate point back up into magnetosphere
- form electron "curtains" around the Earth.

THUNDERSTORM RUNAWAY BREAKDOWN

- The quasielectrostatic field from the lightning discharge is calculated taking a positive point or disk charge Q at 10 km, negative $-Q$ at 5 km, and removing the positive charge to the ground, as shown in **Figure 1(a)**.

- Runaway electron density:

$$v_R \frac{dN_R}{dz} = RN_R + S_0(z)$$

where $v_R \approx 0.9c$, the growth rate R is calculated using the Monte Carlo model [*Lehtinen et al.*, 1999], $S_0(z)$ is the source of energetic electrons from cosmic rays.

- Calculations show that the flux entering the ionosphere is insignificantly changed by the geomagnetic field for latitudes $> 45°$.

- The density of the beam entering the ionosphere depends strongly on Q, especially for a point charge (**Figure 2**).

- Electron distribution and an analytical fit are shown in **Figure 2**. It was calculated using the Monte Carlo model for $Q = 500$ C. The calculations show that we can neglect the $p_\perp$ component compared to $p_z = p_\parallel$.

- Number of electrons entering the ionosphere is calculated assuming the transverse beam size to be the same as the disk charge size ($\sim$12 km for $Q = 500$ C), the process duration 1 ms.

BEAM-PLASMA WAVE INTERACTION

- The energetic electron beam entering the ionosphere can interact with plasma waves in the magnetosphere before it precipitates at the conjugate point, as shown in **Figure 1(b)**.

- Beam-plasma permittivity for a 1D relativistic beam:

$$\epsilon(k,\omega) = 1 - \frac{\omega_0^2}{\omega^2} - \omega_0^2 \frac{N_R}{N} \int \frac{(1-\beta^2)^{3/2} f(p) dp}{(\omega - kc\beta)^2},$$

  where $N = 10^9$ m^{-3} is the magnetospheric plasma density, ω_0 is the magnetospheric plasma frequency.

- Analytical fit shown in **Figure 3**:

$$f_{\text{fit}}(p) = \frac{1}{p} \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{ -\frac{1}{2\sigma^2} \left[\ln\left(\frac{p}{p_0}\right) \right]^2 \right\}$$

- The maximal wave growth rate of the kinetic hot beam — cold plasma instability was obtained at $\omega \approx \omega_0$ using $f_{\mathrm{fit}}(p)$:

$$\mathrm{Im}\ \omega \approx 25\omega_0 \frac{N_R}{N}$$

- Interaction with plasma becomes important for $N_R \gtrsim 100\ \mathrm{m}^{-3}$.

PRECIPITATION AND BACKSCATTER

- Precipitating energetic ($\sim$ several MeV) electrons are studied using Monte Carlo simulation.

- The momentum distribution of precipitating electrons is assumed to be the same as when they left the atmosphere at the conjugate point (**Figure 3**). The simulation starts at 700 km.

- Most electrons slow down, but some turn around and get into the ionosphere again, i.e. "backscatter". The phase space snapshot at the moment when the beam hits the atmosphere is provided in **Figure 4**. The number of electrons with energy > 2 keV and their average altitude are shown in **Figures 5, 6**.

- The backscattered electrons form a “curtain” when they undergo longitudinal drift around the Earth, as in **Figure 7**.

OPTICAL EMISSIONS

The optical emissions of molecular bands is calculated using a steady-state solution for excited state populations [*Bell et al.*, 1995]:

- First Positive N_2 group (1P)
- Second Positive N_2 group (2P)
- First Negative N_2^+ group (1N)
- N_2^+ Meinel group (M)
- First Negative O_2^+ group (1N)

The forbidden "auroral" lines are calculated by solving the time-evolution equations for excited state populations:

- Red O line at 6300 Å
- Green O line at 5577 Å

The results of calculations are shown in **Figure 8**.

GAMMA RAYS

The upward-going gamma rays are the result of bremsstrahlung by the backscattered electrons. The flux at 500 km altitude as a function of time in four different photon energy ranges is shown in **Figure 9**. The flux detectable by the BATSE satellite on CGRO is $\sim 10^4$ ph m^{-2} s^{-1}.

CONCLUSIONS

- We calculated the energetic electron flux, originating from a thunderstorm and precipitating at the geomagnetically conjugate point.

- The interaction of the beam with the ionospheric plasma is negligible.

- To get detectable optical emissions ($\sim$1 kR) at the conjugate point, we need a large source discharge, $Q > 500$ C.

- The molecular bands have much more intensity than the atomic oxygen auroral lines, unlike for long-lasting auroras, because of the short duration of the process.

- For large energetic electron density $N_R \gg 200$ m^{-3}, plasma wave instabilities in the magnetosphere can be significant. Assuming

that the electrons have been scattered isotropically at the equatorial plane, the downward flux at the conjugate point is approximately proportional to the cosine of the pitch angle:

- most electrons ($\sim 90\%$ for 45° latitude) remain in the radiation belts;
- the fraction of the backscattered electrons is greater;
- both optical and gamma ray emissions are more extended in time.

- The results with assumption of isotropically scattered electrons in the equatorial plane are presented in **Figure 10**. To ease the comparison with a narrow beam, the number of electrons entering the ionosphere is taken the same as in previous Figures.

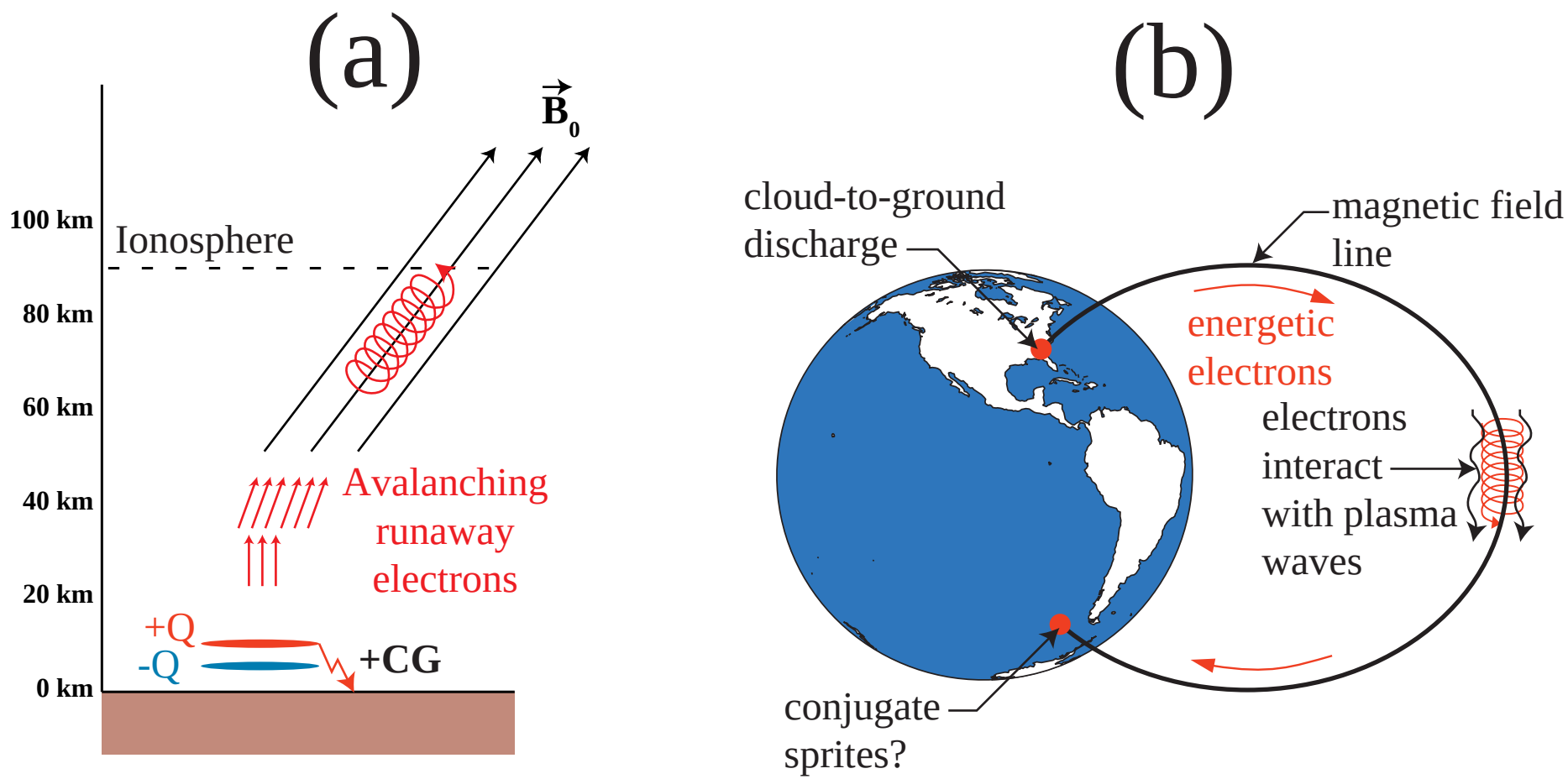


Figure 1. (a) Configuration of the discharge. (b) Electron precipitation at the conjugate point.

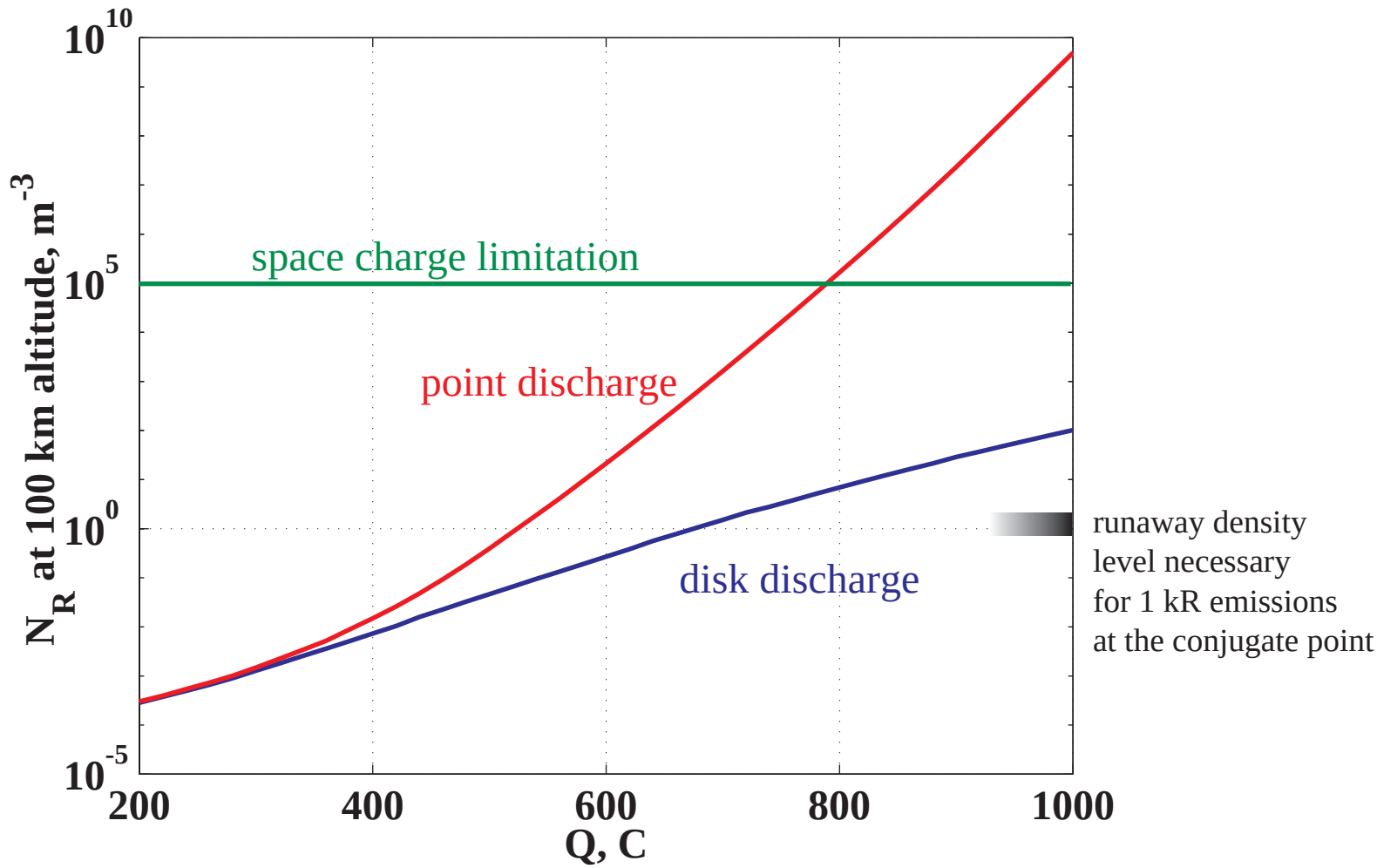


Figure 2. Density of the runaway electron beam entering the ionosphere as a function of the discharge magnitude.

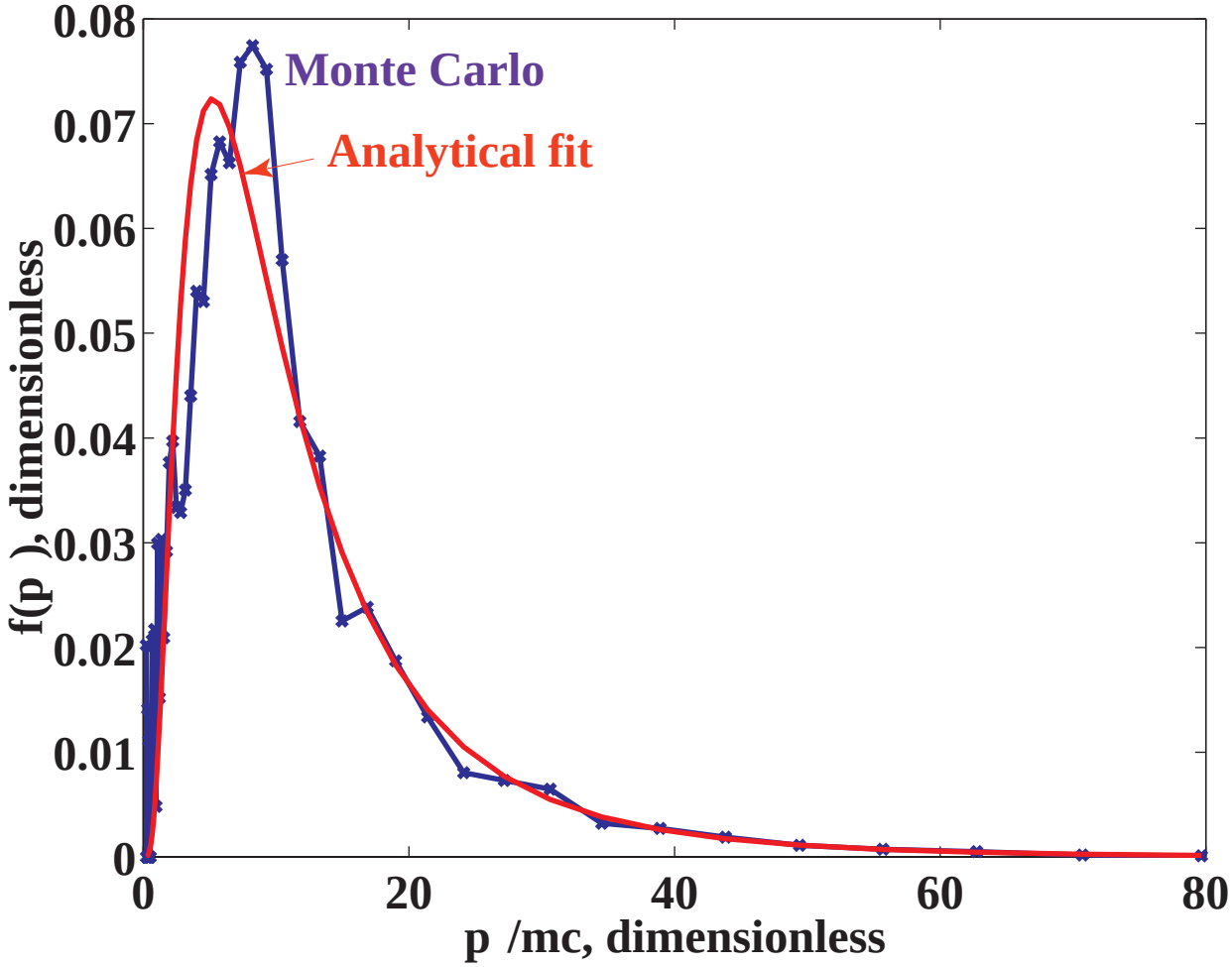


Figure 3. Electron distribution function.

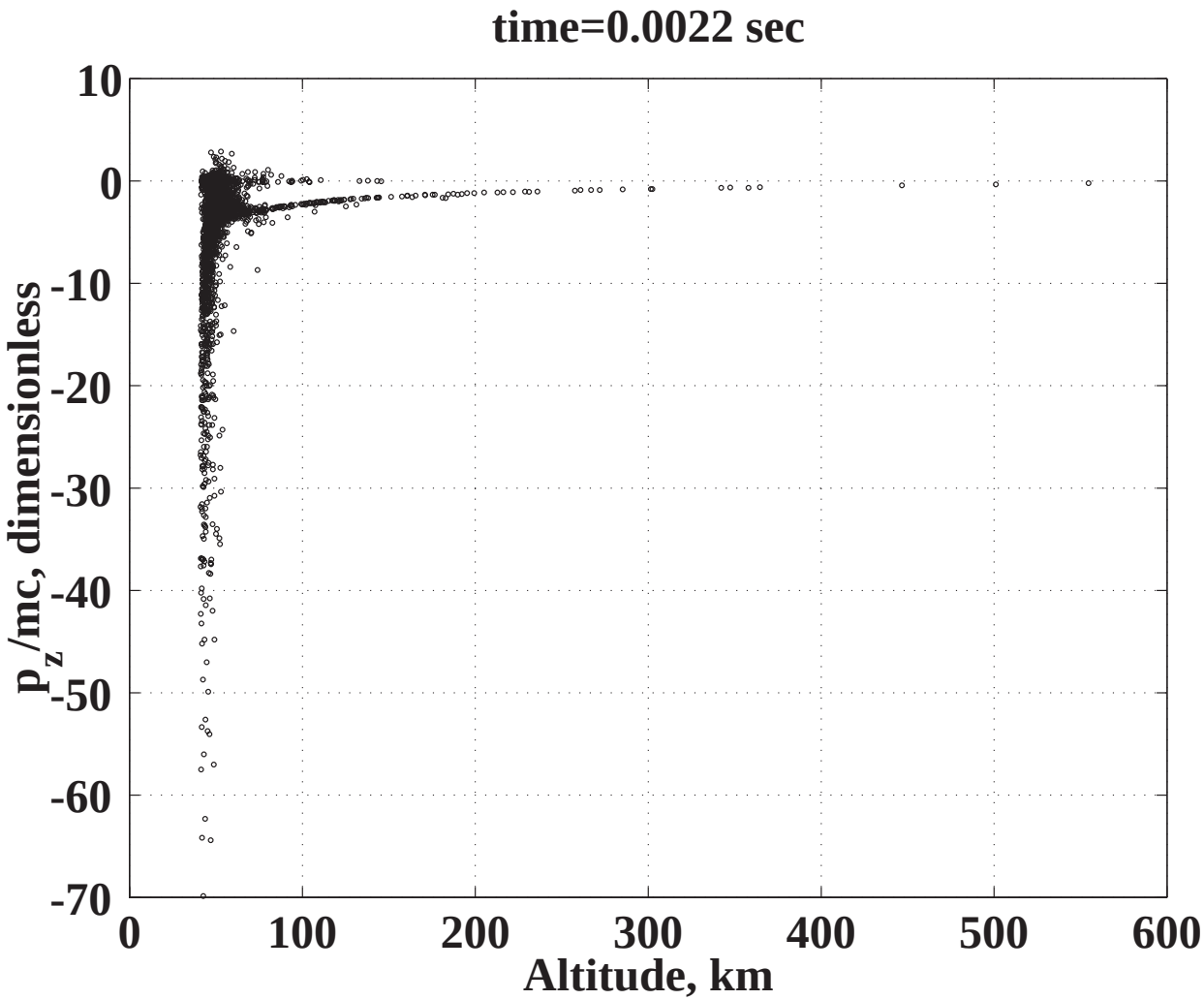


Figure 4. Electron phase space snapshot.

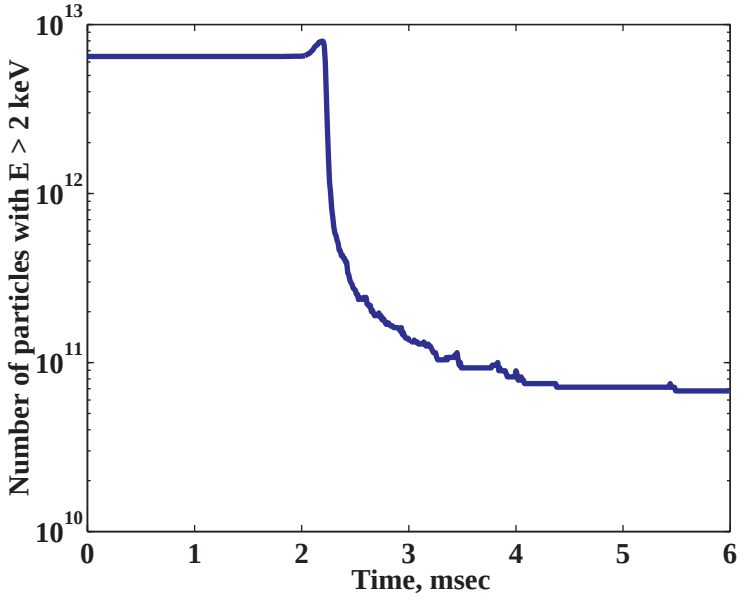


Figure 5. Number of precipitating and backscattered electrons with energies > 2 keV.

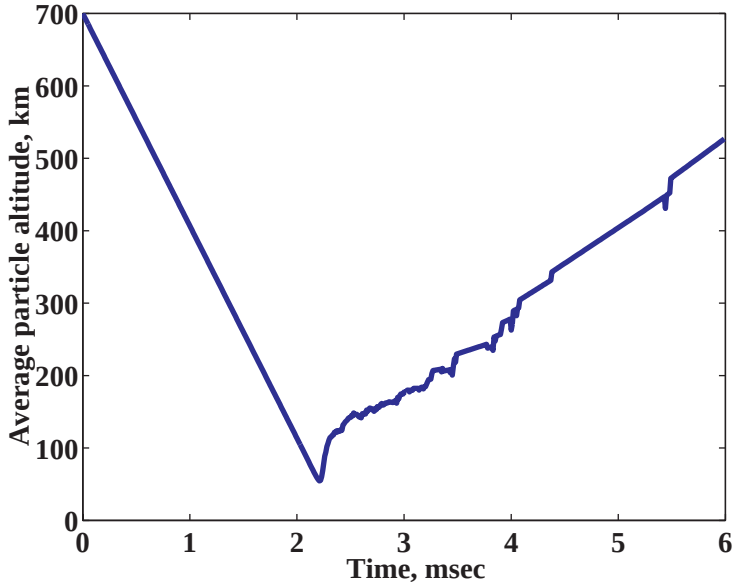


Figure 6. Average altitude of the electrons with energies > 2 keV.

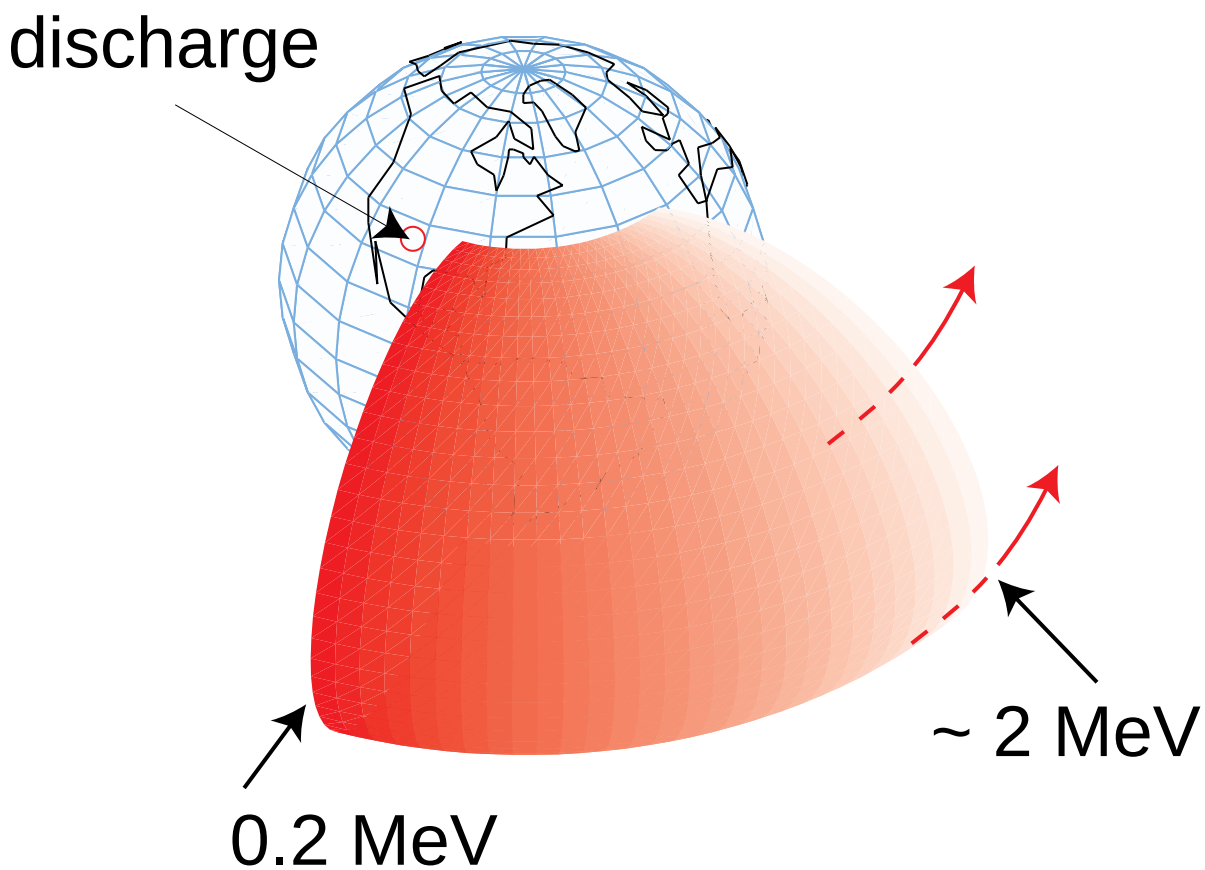
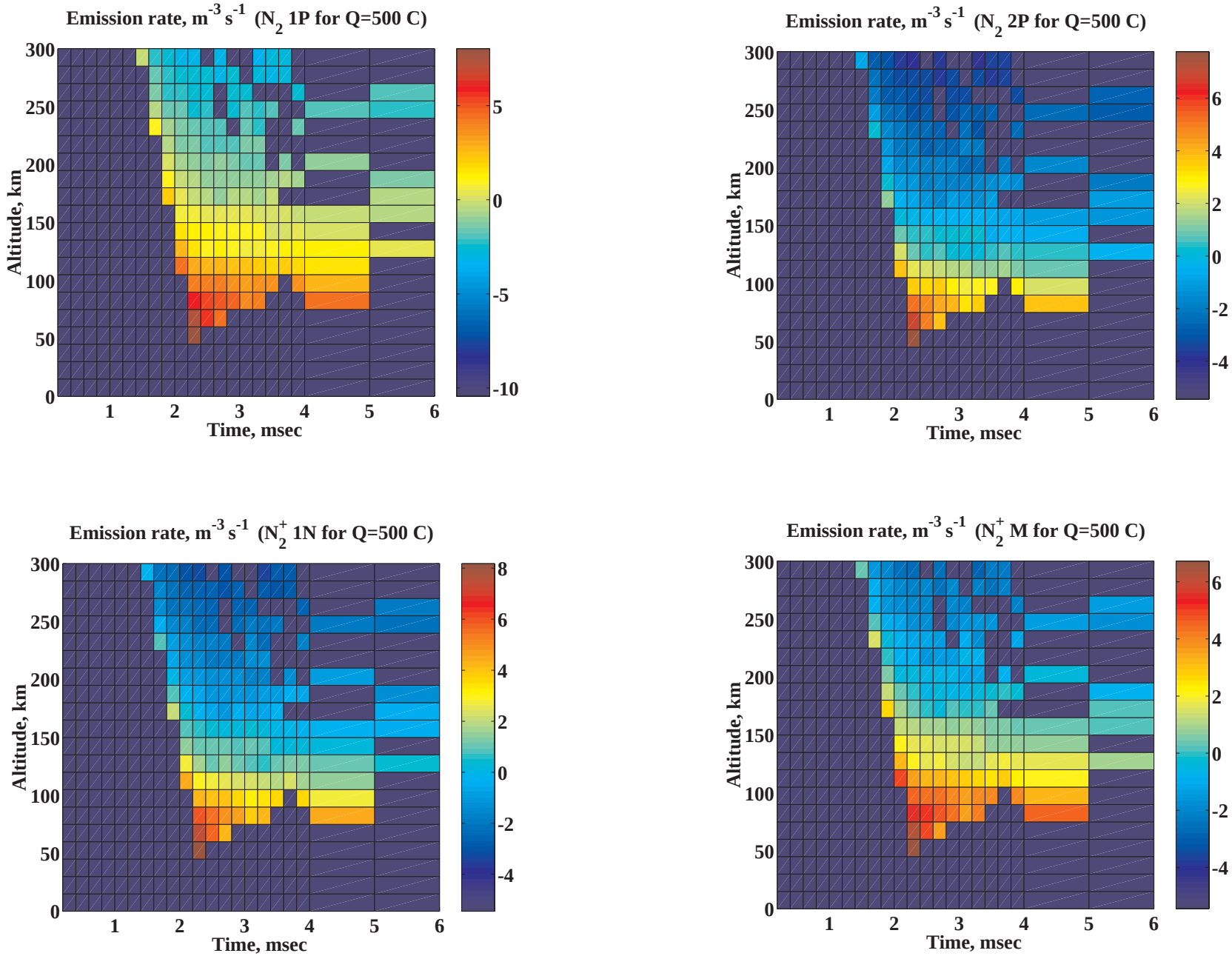
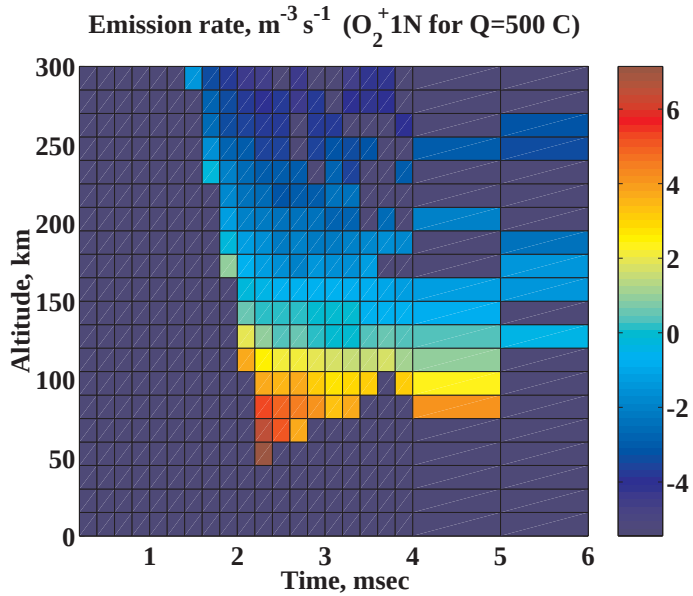


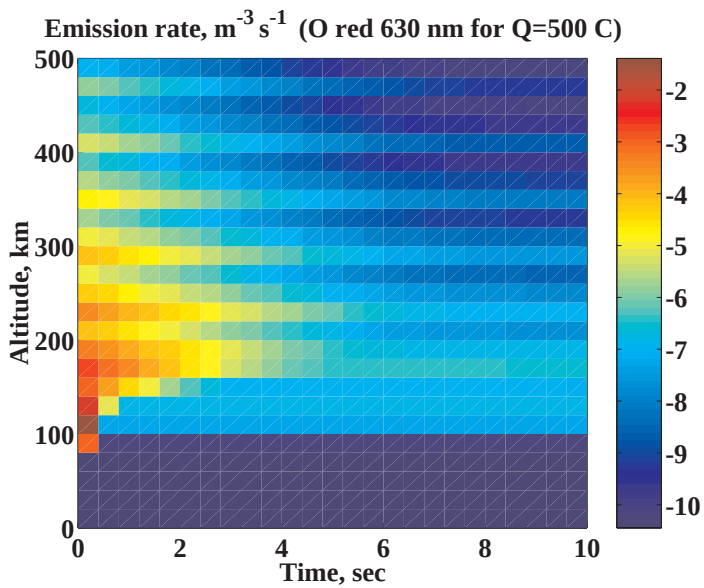
Figure 7. A curtain produced by the backscattered energetic electrons due to longitudinal drift dispersion.

(a) molecular bands





(b) auroral atomic oxigen lines



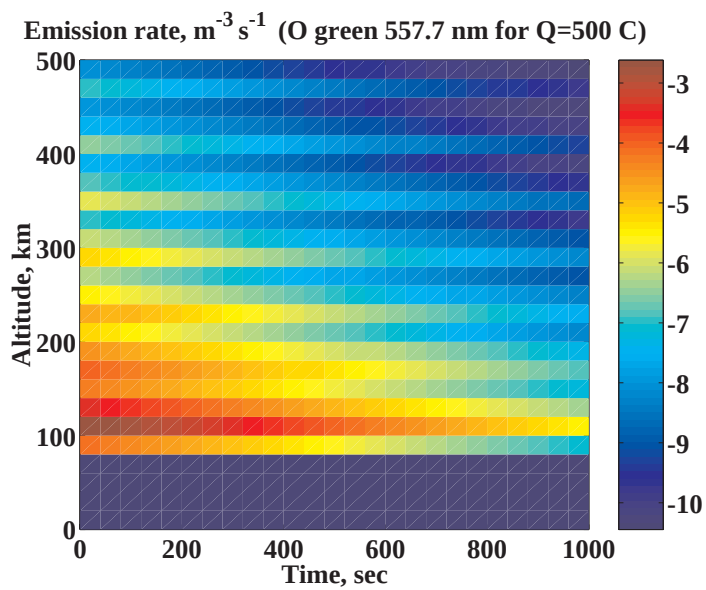


Figure 8. Optical emissions excited by the precipitating electrons.

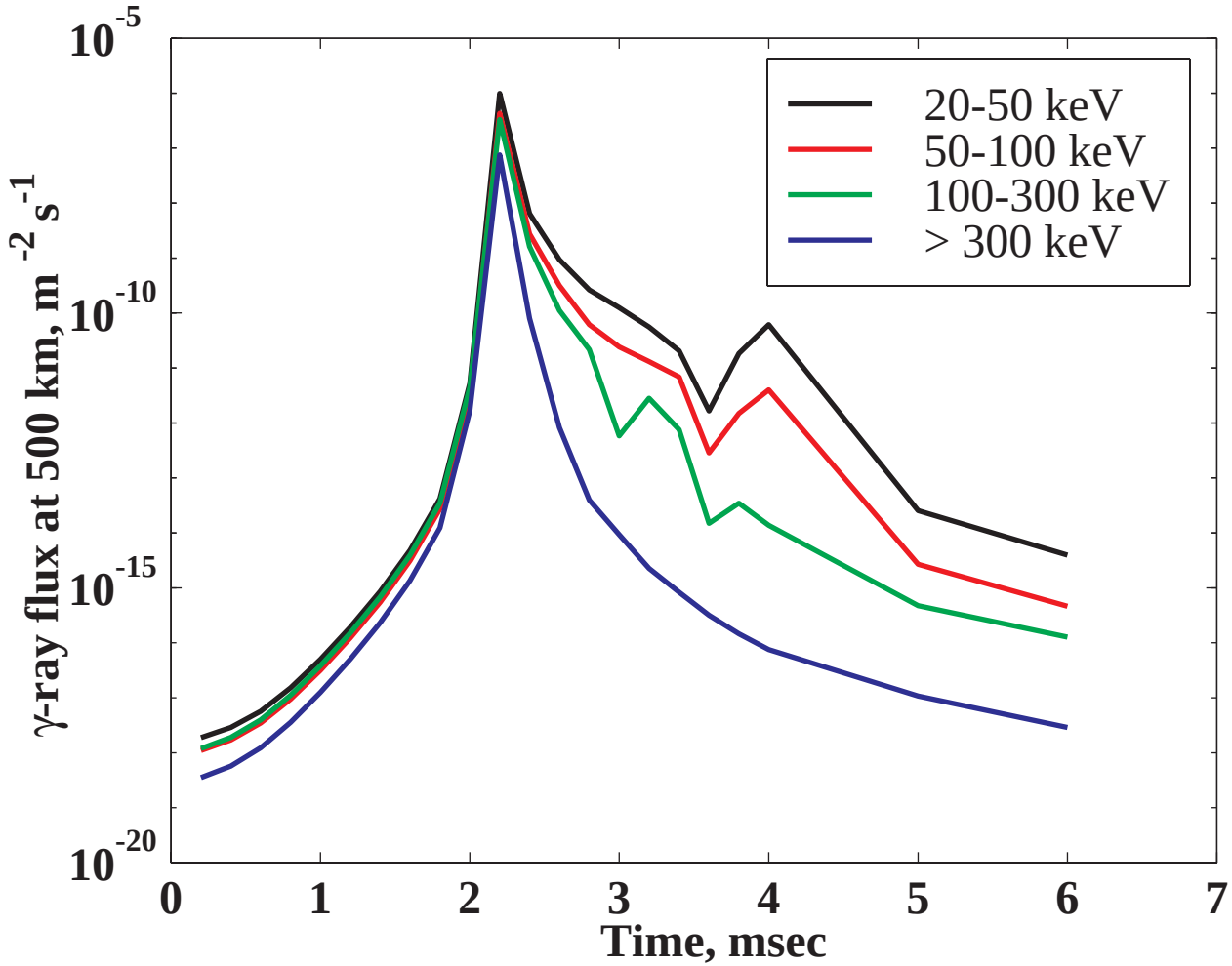


Figure 9. Upward gamma ray flux from precipitating electrons.

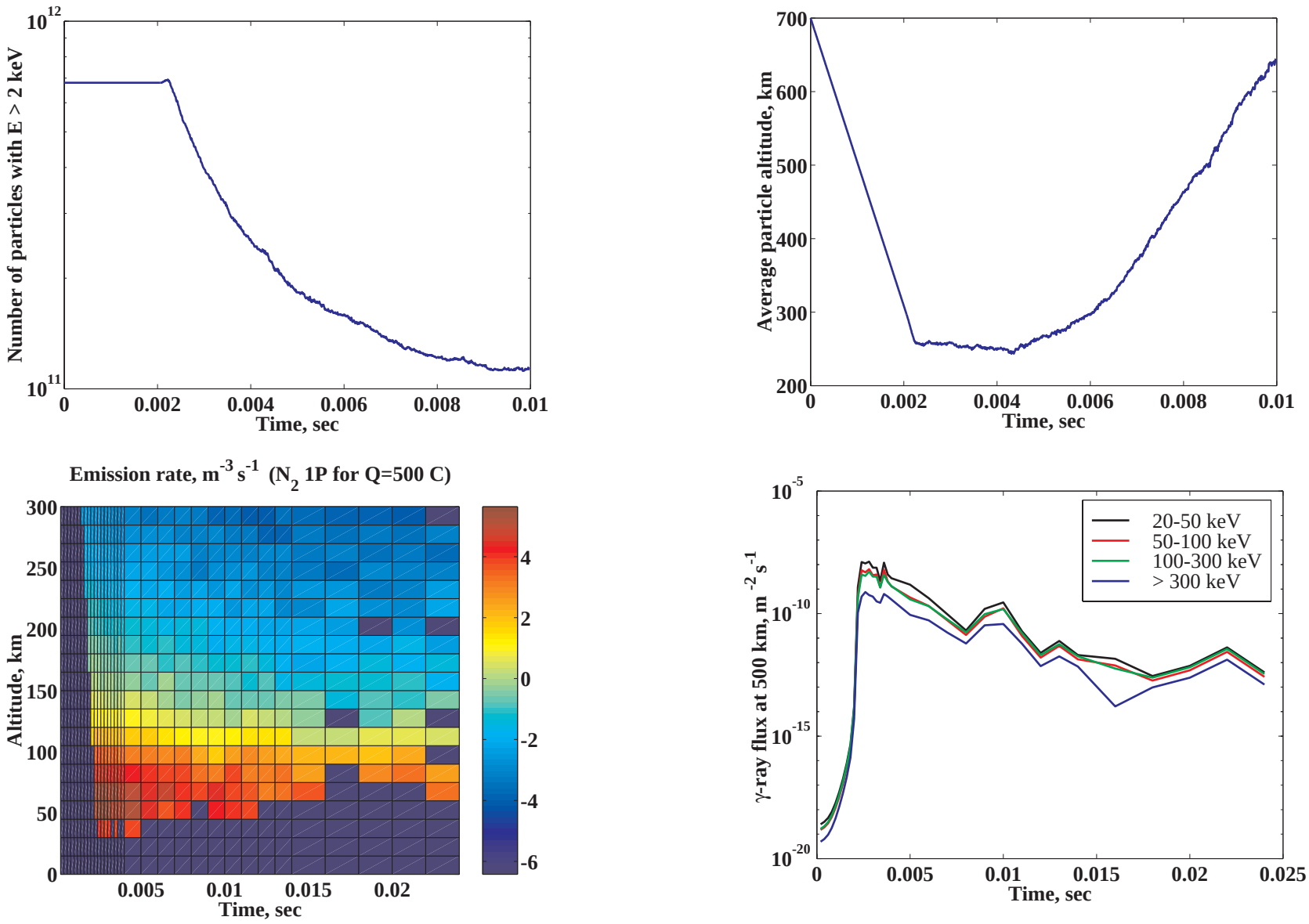


Figure 10. Basic results for the same discharge but isotropic electron distribution at the equator.

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