Two-Dimensional
Driven by Quasi

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Model of Runaway E
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N. G. Lehtinen

R Laboratory, Stanford, CA 94305

Electron Beams
ercloud Fields

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INTRODUCTION

- As shown in **Figure 1**, the phenomena of lightning-mesosphere-ionosphere interactions include **Blue Jets**, **Elves**, **Red Sprites**, and **terrestrial γ-ray flashes (TGF)**. This paper investigates the role of avalanching **runaway electrons (REL)** in the last two processes.
- The Sprite type of luminous discharge is most commonly observed with sharp features and vertical structure, with response primarily in the red region of the spectrum, exhibiting short ($\sim$1–10 ms) duration, and generally detached from the cloud-tops but extending to as high as 95 km altitude [*Sentman et al.*, 1995].
- Recently *Pasko et al.* [1997a; hereafter referred to as I] proposed that Sprites are produced by the heating of mesospheric electrons by large **quasi-electrostatic (QE)** thundercloud fields $\vec{E}$. QE fields appear following a +CG light-

ning discharge, and their duration is controlled by the local relaxation time [I]. This mechanism accounts for many of the observed aspects of these discharges but does not explain emissions below 60 km which some Sprites exhibit.

- In the present work, we explore the possibility that high energy (20 keV-10 MeV) runaway electrons (REL) may be involved in producing the low altitude portion of the optical output associated with Red Sprites (**Figure 1**). We examine this question within the context of the REL-QE model.
- Besides optical emissions, REL may also be responsible for γ-ray emissions [*Lehtinen et al.*, 1996] detected by the Burst and Transient Source Experiment (BATSE) detectors, located on the Compton Gamma Ray Observatory (CGRO), which are described by *Fishman et al.* [1994]. Since these flashes are associated with thunderstorm centers and in a few cases have been correlated with individual lightning

flashes [*Inan et al.*, 1996], they may be caused by the runaway electrons.

REL-QE MODEL

- The initial thundercloud charge consists of $\pm\ Q$ at altitudes of 10 km and 5 km respectively. The separated dipole charges are assumed to form over a large time ($>$ 100 s). The induced static charge distribution is calculated using the electrostatic heating (ESH) model [*Pasko et al.*, 1997b]. Subsequently the positive part of the dipole charge is discharged to ground with a time constant of$\sim$ 1 ms.
- The dynamics of the charge distribution is calculated using the QE model [I], but taking into account the REL field and the change of conductivity associated with the low energy secondaries produced by the REL.
- The effects of the **geomagnetic field** $\vec{B}_0 \sim 5 \times 10^{-5}$ T, assumed to be vertical in the model to preserve cylindrical symmetry, on the electron component of the conductivity of the atmosphere and the motion of REL are included.

RUNAWAY ELECTRONS

- Transport equation for REL:

$$\frac{\partial N_R}{\partial t} + \mathrm{div}(\vec{v}_R N_R) = \frac{N_R}{\tau_i} + S_o(z)$$

  N_R is the number density of the REL, $|\vec{v}_R| \sim c$ is their mean velocity, $1/\tau_i$ is the runaway production rate, S_o is the local source function for energetic cosmic ray secondary electrons.
- $1/\tau_i$ is a function of $\delta_0 = E/E_t$, and is negative for $\delta_0 < 1$ and positive for $\delta_0 > 1$. E_t is the runaway threshold field [*Roussel-Dupré et al.*, 1994].
- REL velocity direction:

$$\frac{v_{Rr}}{v_{Rz}} = \frac{E_r}{E_z}(1 + \omega_{HR}^2/\nu_R^2)^{-1}$$

  $\omega_{HR} \sim \omega_H$ is the REL gyrofrequency,
  $\nu_R = F_D(p)/p$ is effective collision frequency.
  $\vec{v}_R \parallel \vec{B}_0$ at $\gtrsim 20$ km and $\vec{v}_R \parallel \vec{E}$ at $\lesssim 20$ km (see **Figure 2**)

- REL are produced by impact ionization of neutrals, and the resulting ions are left behind as positive space charge.
- Most of the free secondary electrons produced as a result of impact ionization of neutrals do not become REL themselves, but are left behind, contributing to the **ionization of the atmosphere**.

OPTICAL EMISSIONS

The optical emissions are produced as a result of excitation of neutral species through impacts by:

- thermal electrons, driven by the electric field, and
- suprathermal electrons ($\gtrsim 10$ eV), created by REL [*Bell et al.*, 1995].

The intensity of each optical line, measured in Rayleighs, is obtained by integrating the emission rate along the line of site.

BREMSSTRAHLUNG

- γ-ray production is characterized by the *doubly differential cross-section* for bremsstrahlung [*Heitler*, 1954] – the cross-section of the bremsstrahlung process into a unit solid angle and a unit photon energy interval). The angular distribution of emission is forward-directed for relativistic electrons. For N_2 and O_2 and for electron initial and final kinetic energies $\sim$1 MeV we can use the Born approximation.
- For propagation from altitudes 60–70 km, where most of the γ-rays are produced, the attenuation of radiation, due to Compton scattering and photoelectric effect, is small ($\leq 1\%$) [*Lehtinen et al.*, 1996].

RESULTS

- **Figure 3** shows the REL beam horizontal and vertical structure. The effects of REL diffusion in velocity space due to ionizing collisions and collisions with nuclei do not lead to significant widening of the beam in our model.
- Optical emissions are mostly due to the thermal electrons, driven by the electric field.
- **Figures 4,5** present the intensity of the N_2 First Positive band. In **Figure 4**, the earlier and wider part of the emissions at altitutes 80–90 km also occurs without including REL into the model and is due to the QE heating of ambient electrons. The later and narrower part, occurring at altitudes 50–80 km is due to ionization by REL.
- **Figure 6** shows the predicted γ-ray fluxes at 500 km height as a function of horizontal distance R_s from the beam location. The results are consistent with 1-d model predictions

[*Lehtinen et al.*, 1996] and BATSE observations [*Fishman at al.*, 1994]. Also, a significant fraction of the γ-ray bursts presented by *Fishman et al.* [1994] have a duration of 3–5 ms, which also agrees with present calculations.

DISCUSSION

- For exponential ambient conductivity profile, the REL avalanche takes place above the formed at 25–40 km negative screening charge of the thundercloud. The production of REL depends exponentially on Q and is sensitive to the ambient conductivity profile.
- The 2-d model predicts the radius of the REL beam of the order 10–15 km, (see **Figure 3**) which is determined mainly by the structure of the post-discharge quasi-electrostatic field.
- The long enduring emission intensity (**Figure 5b**) is due to persistent high $\vec{E}$ at the lower boundary of the highly conducting column of ionization created by the REL. This boundary propagates down to ~ 40 km at later times (20–30 ms) after the discharge due to runaway and conventional breakdown.

- The optical emissions are consistent with the characteristics of Sprites, in particular the carrot-shaped and columnar type [*Sentman et al.*, 1995]. As shown in **Figure 5a**, the optical emissions due to REL tend to peak in the 55–70 km altitude range, and substantial intensity can be found at altitudes as low as 45 km. Thus the predictions of the REL model fit the observations reasonably well.
- In comparison with other mechanisms, we note that the predicted optical emissions for QE heating of ambient electrons [I] peak at 80–95 km altitude and have no significant intensity below 60 km.
- Major features of the BATSE γ-ray observations can be explained by the runaway MeV electron model.

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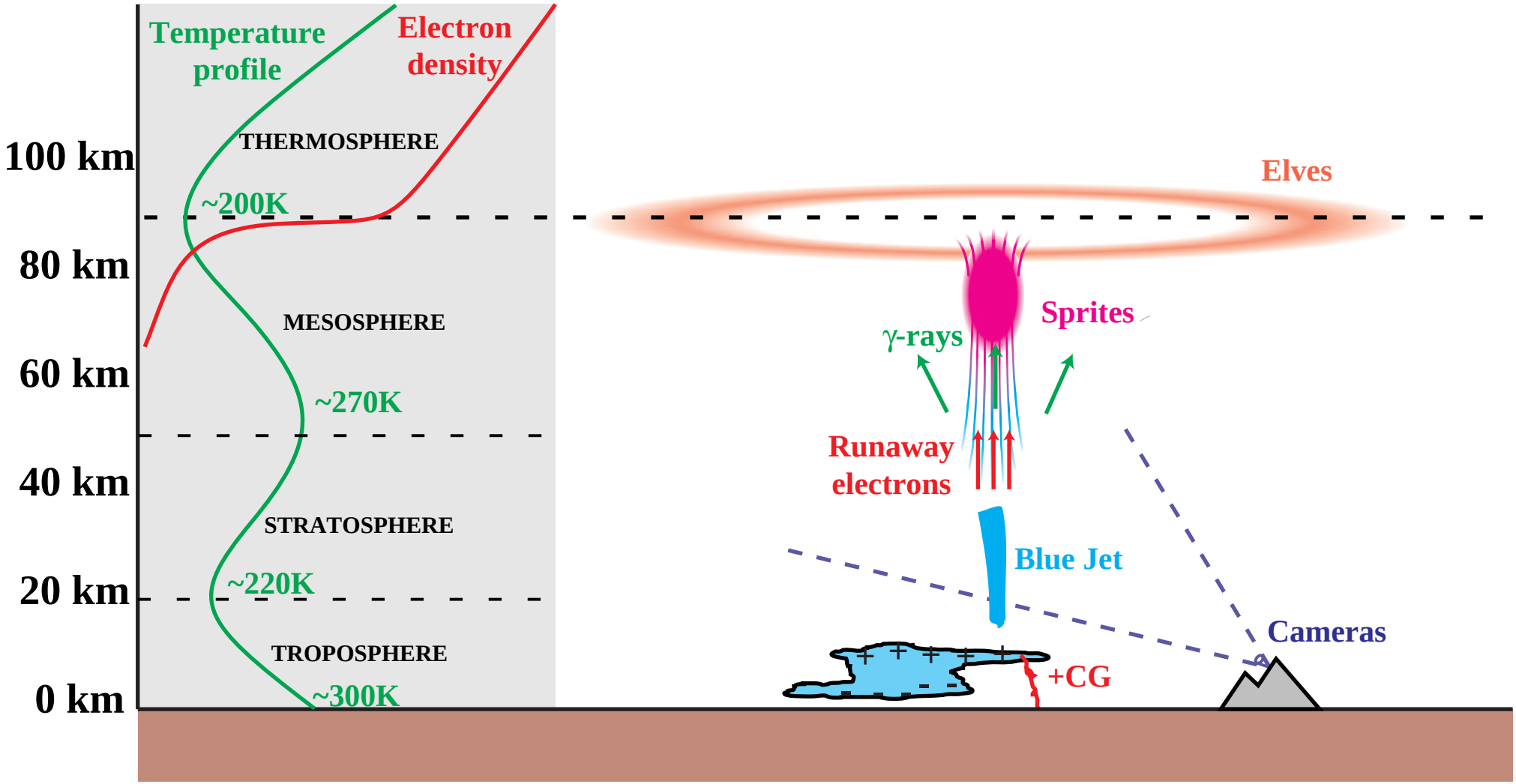

Fig. 1. Lightning-mesosphere interaction phenomena.

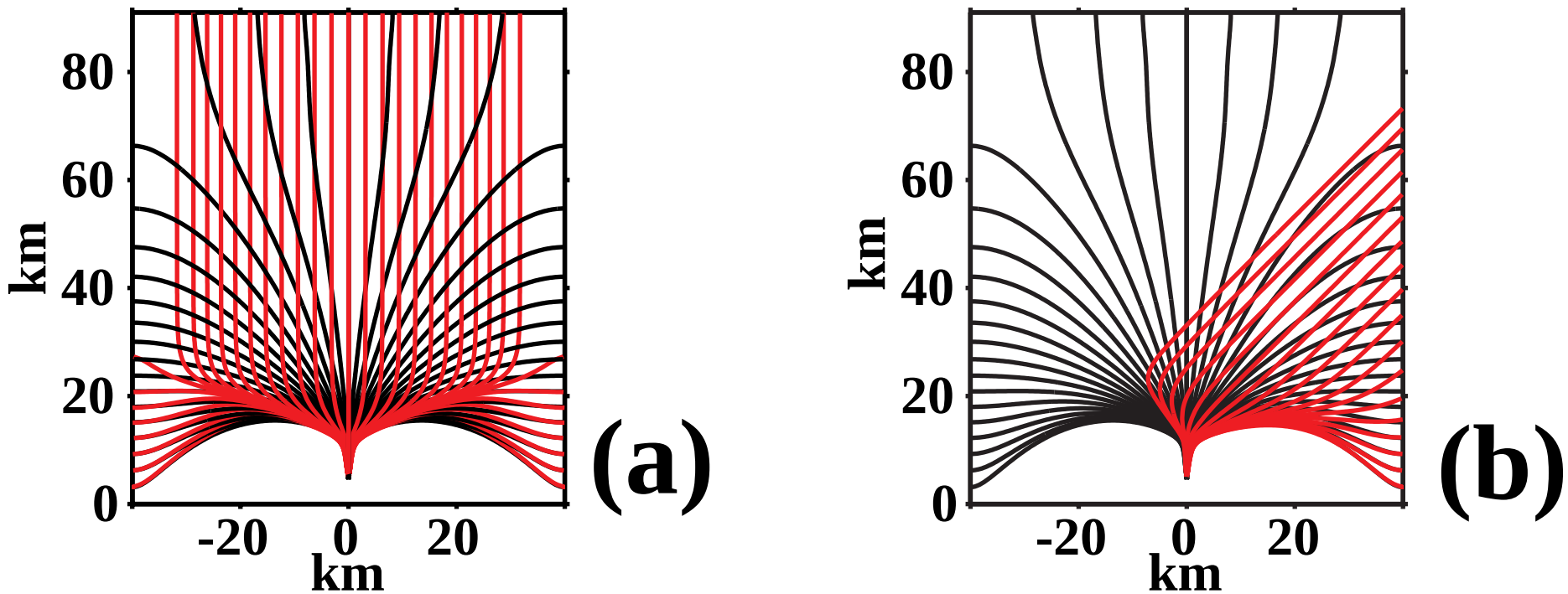

Fig. 2. Electric field lines (black) and REL velocity lines (red) at t=1.2 ms (maximum REL density), *Q*=225 C: (a) vertical geomagnetic field (our model); (b) geomagnetic field tilted at 45ßto the vertical.

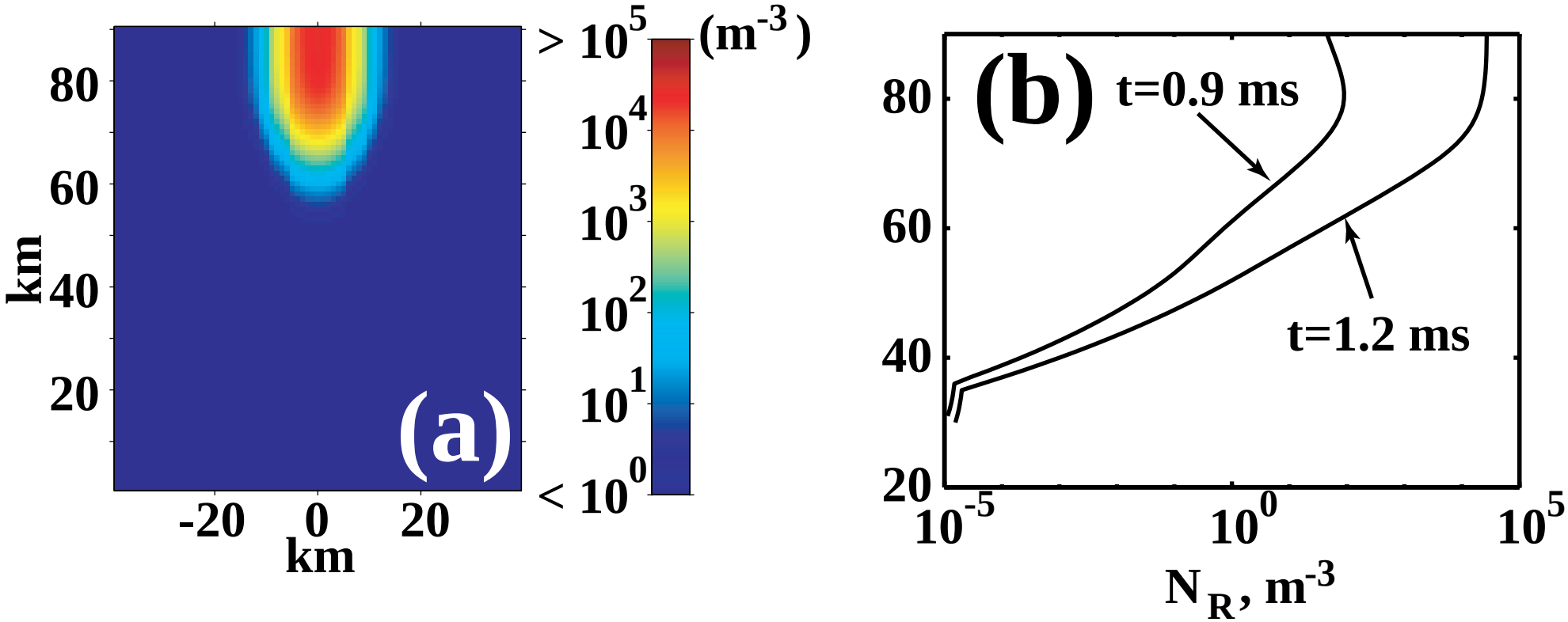

Fig. 3. REL density (*Q*=225 C):
(a) 2D plot at t=1.2 ms (maximum number of REL)
(b) on the axis of the model

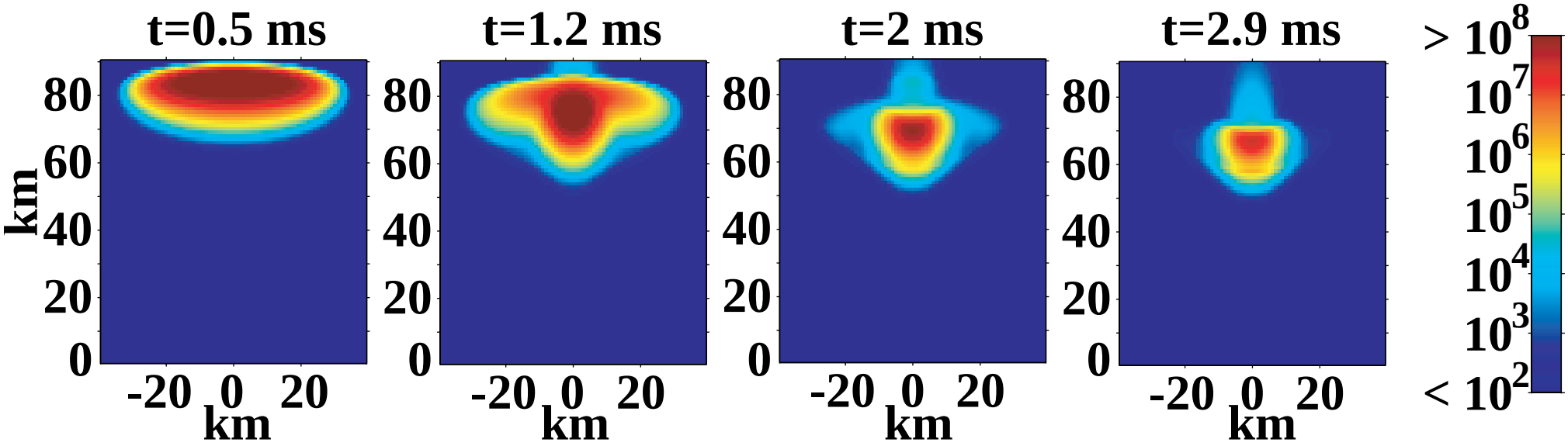

Fig. 4. 2D plots of the intensity of the First Positive N_2 band (in Rayleighs).

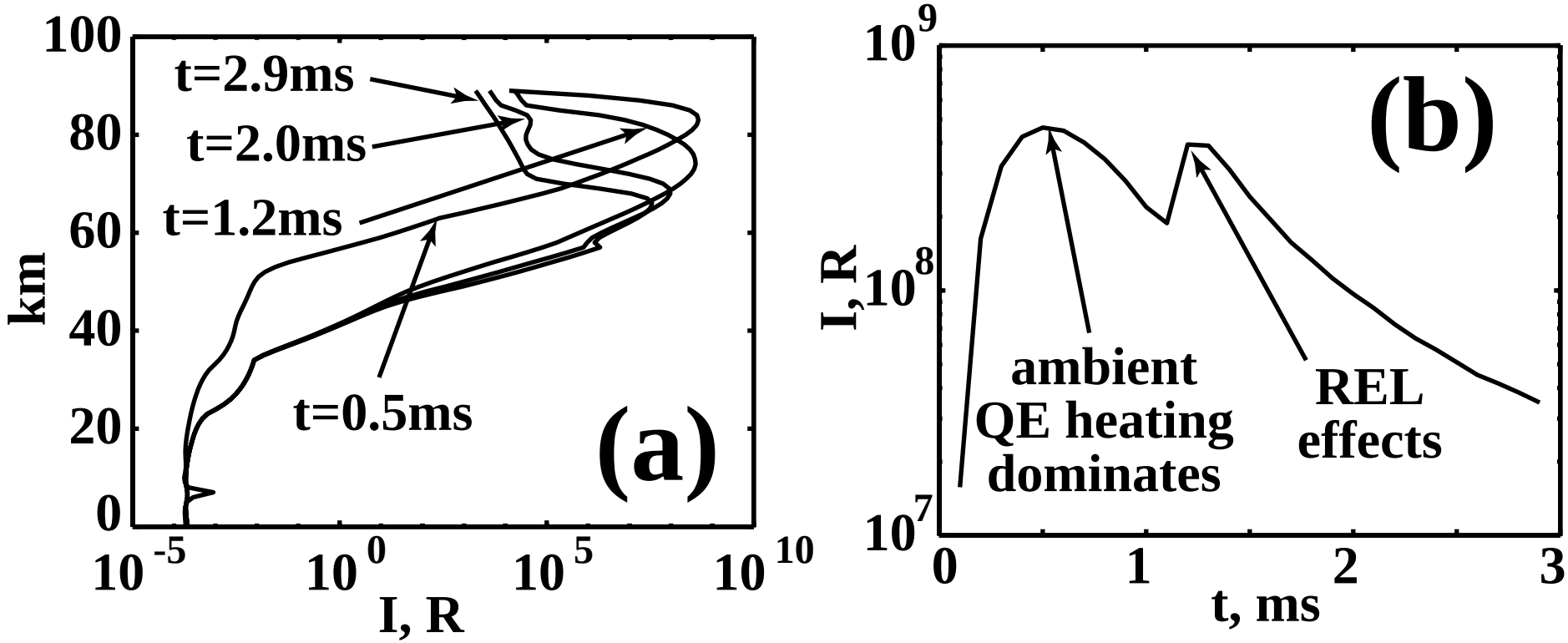

Fig. 5. Intensity of First Positive N_2 band in Rayleighs (Q=225 C):
(a) on the axis at different moments in time;
(b) maximum intensity.

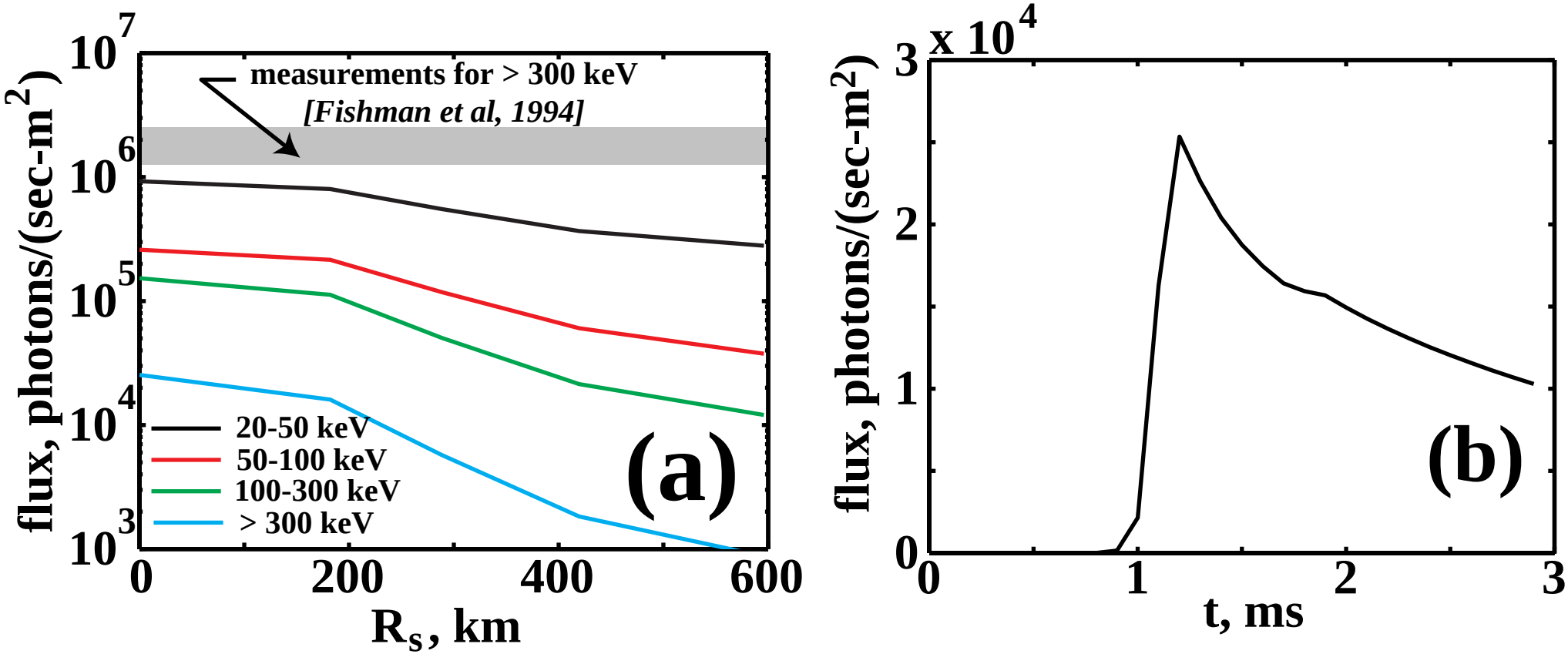

Fig. 6. REL γ-ray emission fluxes at the CGRO height, integrated over BATSE energy ranges (Q=225 C): (a) dependence on horizontal range at t=1.2 ms (maximum emission); (b) flux exactly above the source (>300 keV).

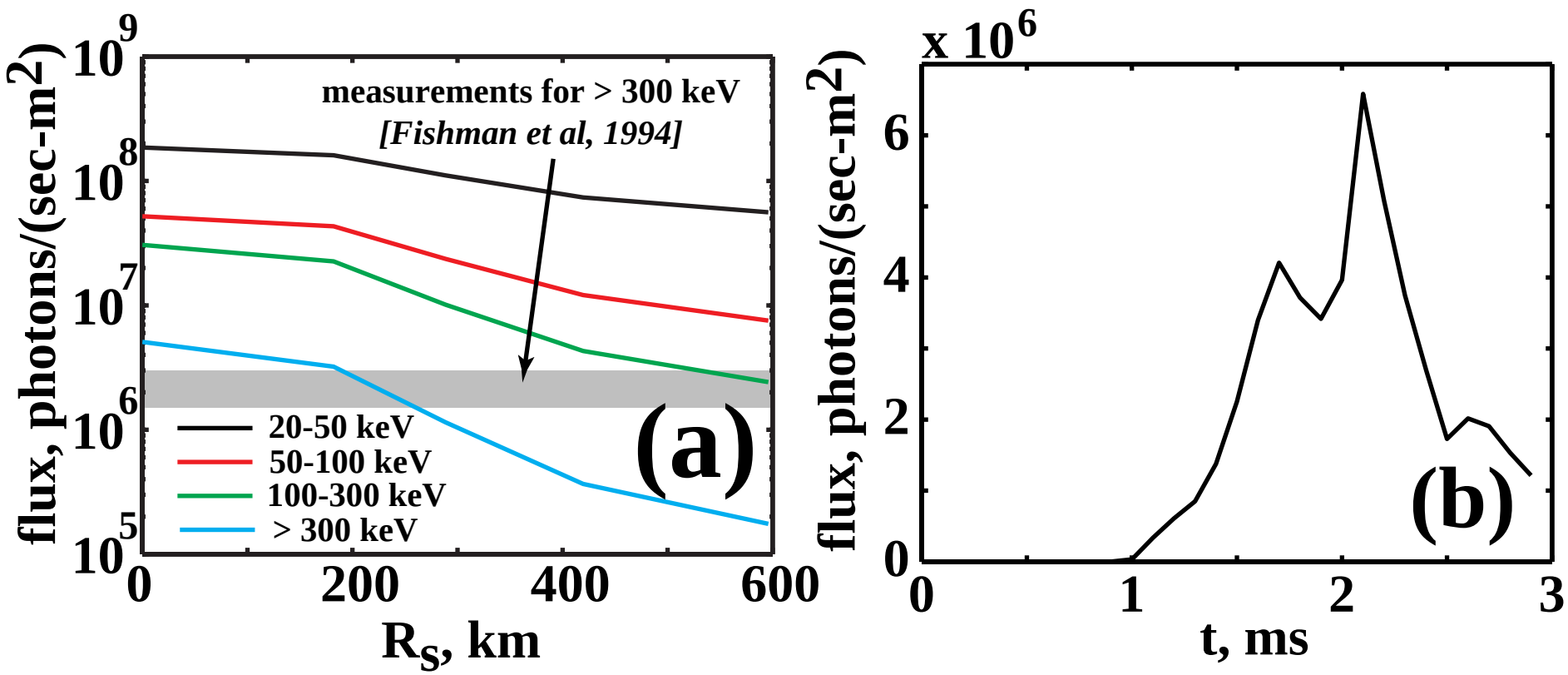

Fig. 7. REL γ-ray emission fluxes at the CGRO height, integrated over BATSE energy ranges (Q=240 C): (a) dependence on horizontal range at t=2.2 ms (maximum emission); (b) flux exactly above the source (>300 keV).