An estimate of the spectral intensity expected from molecular Bremsstrahlung radiation in extensive air showers

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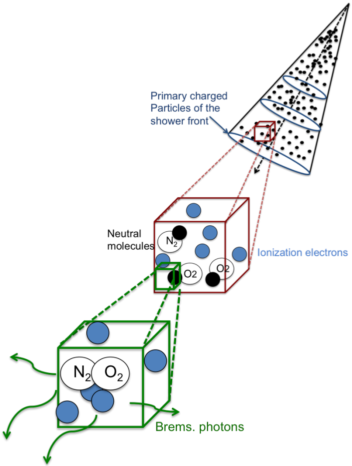
Outline

Motivation

Depict analytically the MBR mechanism

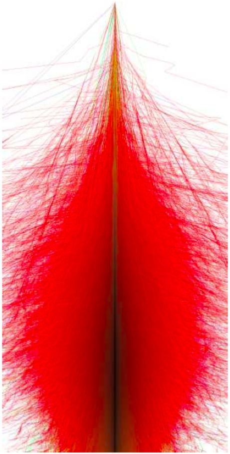
- Evaluation of the number of primary charged particles in an EAS
- Production of ionization electrons and their time evolution
- MBR emission using the free-free approach



Total number of primary e$^+$/ e$^-$ per unit surface

$$n_{e,p}(r,a) = N_{e,p}(a) \frac{ldf(r,a)}{2\pi \int dr\ r\ ldf(r,a)}$$

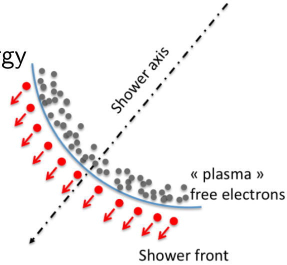
- Total number of primaries at altitude a using Gaisser-Hillas formula
- NKG function describing the lateral distribution (LDF)



In this study, parameters are tuned to apply to a vertical shower with energy $10^{17.5}$ eV to compare with [1].

- Presence of a weakly ionized plasma
- Number of ionized electrons per unit length per energy band

$$\frac{d^2N_{e,i}}{da\ dT_e}(a,T_e) = \rho_m(a)\ f_0(T_e) \left\langle \frac{dE}{dX} \right\rangle \frac{1}{I_0 + T_e}.$$



with parametrization from [2] :

$$f_0(T_e) = \frac{K}{1 + (T_e/\overline{T})^{2.1}}$$

is the distribution in kinetic energy of the resulting ionization electrons and $\left\langle \frac{dE}{dX} \right\rangle$ the mean energy loss of primary electrons per grammage unit

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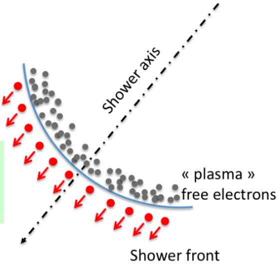


➡ *Instantaneous* flux of ionization electrons per kinetic energy band

$$\phi^0_{e,i}(r,a,T_e) = \frac{c\beta(T_e) f_0(T_e)}{2(I_0+T_e)} \left\langle \frac{dE}{dX} \right\rangle \rho_m(a)\ n_{e,p}(r,a).$$

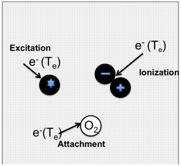
- Time evolution of the flux of ionization electrons fully encompassed in the energy distribution time evolution $f(T_e, t)$
- Boltzmann equation accounting for all interactions at work

Assumptions :

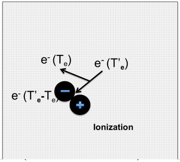
- Ionization electrons static in space (low energy electrons, rate of disappearence ∼100 ns)
- Neglect absorption effects

➡ Solving Boltzmann equation

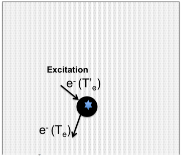
$$\frac{\partial f}{\partial t}(T_e,t) = -n_m(a)c\beta(T_e)\Big(\sigma_{\rm att}(T_e)+\sigma_{\rm exc}(T_e)+\sigma_{\rm ion}(T_e)\Big)f(T_e,t)$$
$$+\, n_m(a)c\int_{T_e}^{T_e^{\rm max}} dT'_e\beta(T'_e)\Big(\frac{d\sigma_{\rm ion}}{dT_e}(T'_e,T_e)+\frac{d\sigma_{\rm ion}}{dT_e}(T'_e,T'_e-T_e)\Big)f(T'_e,t)$$
$$+\, n_m(a)c\int_{T_e}^{T_e^{\rm max}} dT'_e\beta(T'_e)\frac{d\sigma_{\rm exc}}{dT_e}(T'_e,T_e)f(T'_e,t)$$



$-n_m(a)c\beta(T_e)\big(\sigma_{\rm att}(T_e)+\sigma_{\rm exc}(T_e)+\sigma_{\rm ion}(T_e)\big)f(T_e,t)$



$+\ n_m(a)c\int_{T_e}^{T_e^{\rm max}} dT'_e\beta(T'_e)\Big(\frac{d\sigma_{\rm ion}}{dT_e}(T'_e,T_e)+\frac{d\sigma_{\rm ion}}{dT_e}(T'_e,T'_e-T_e)\Big)f(T'_e,t)$



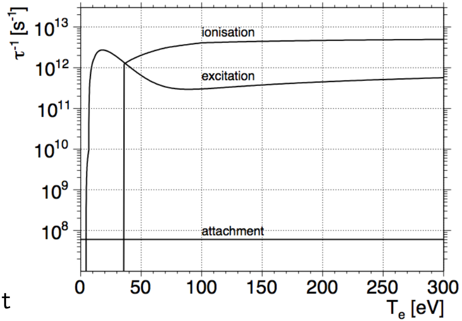
$+\ n_m(a)c\int_{T_e}^{T_e^{\rm max}} dT'_e\beta(T'_e)\frac{d\sigma_{\rm exc}}{dT_e}(T'_e,T_e)f(T'_e,t)$

With σ_i being the cross-sections of interest and n$_m$(a) the density of molecules at altitude a

- Rates of collision $\tau_i^{-1} = n_m(a)c\beta(T_e)\sigma_i(T_e)$
- Process description of attachment, ionization and excitation from [3], [4] and [5] respectively.

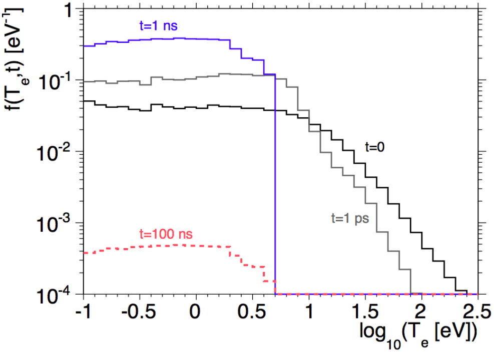
Characteristic time scales :

- τ_{att} = 15 ns (50 ns) at sea level (at a = 6 km)
- $\tau_{ion} \leq$ ps
- $\tau_{exc} \sim$ ps



➡ E > I_0 : Ionization dominant
➡ 4.5 eV < E < I_0 : Excitation dominant
➡ E< 4.5 eV : Attachement, disappearance of e^-

Solution to Boltzmann equation obtained by MC simulation of all processes at work



➡ Quick increase due to ionization

➡ Exponential decrease due to attachment process

$$f(T_e,t) \simeq \tilde{f}_0(T_e)\exp\left(-\frac{t}{\tau_{\text{att}}}\right)$$

with $\tilde{f}_0$ quasi-uniform for T_e in [0,4.5 eV]

➡ Migration of e$^-$ below the lowest excitation threshold of interest in about 1ns

Ionization electrons undergo quasi-elastic collisions with neutral molecules in the atmosphere

$$e^{\pm} + M \rightarrow e^{\pm} + M + \gamma$$

Photon production rate

$$r_\gamma(r,a,t,\nu) = n_m(a) \int_0^{T_e^{\max}} dT_e \; \phi_{e,i}(r,a,T_e,t) \; \sigma_{\text{ff}}(T_e,h\nu)$$

where

- Density of molecules at altitude a
- Flux of ionization electrons
- Free-free cross section : for low-energy electrons and GHz photons $\sigma_{\text{ff}}(T_e,h\nu) \rightarrow \sigma_{\text{ff}}(T_e) = 1.211\ 10^{-8} T_e \sigma_m(T_e)$ (Electron momentum transfer cross-section tables from [6])

The emitted spectral power per volume unit at each point (r, a) :

$$\frac{d^2P}{d\nu dV}(r,a,t) = \frac{d}{d\nu}\left(h\nu\ r_\gamma(r,a,t)\right)$$
$$= \frac{hc\rho_m^2(a)\mathcal{N}_A}{2AI_0}\left\langle\frac{dE}{dX}\right\rangle\tilde{\sigma}\ n_{e,p}(r,a)\exp(-t/\tau_{\text{att}}(a))$$

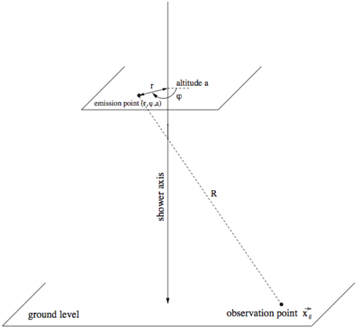
with

$$\tilde{\sigma} = \int_0^{T_e^{\max}} dT_e \frac{I_0}{I_0+T_e}\tilde{f}_0(T_e)\beta(T_e)\sigma_{\text{ff}}(T_e)$$

The effective cross section $\Longrightarrow \tilde{\sigma} \simeq 5\ 10^{-30}\ \text{m}^2$ (Nitrogen target)

Semi analytical expression of the observable spectral intensity at any ground position $\mathbf{x_g}$:

$$\Phi_g(\mathbf{x}_g, t) = \int_0^\infty r dr \int_0^{2\pi} d\varphi \int_0^\infty da \frac{1}{4\pi R^2(r,\varphi,a)} \frac{d^2P}{d\nu dV}(r, a, t_d(t, r, \varphi, a))$$



Considerations :

- Photons are emitted isotropically
- Absorption effects found to be negligible

Do photons get absorbed within the interaction volume ?

Absorption coefficient

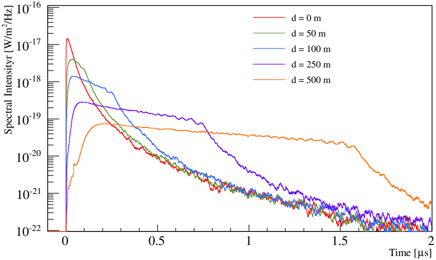
- Defined as the relative attenuation per unit length of EM waves
- Derivation by making use of the detailed balance principle, absorption and spontaneous emission

$\Rightarrow$ Close to shower core and maximum of shower development

$$\alpha_\nu \simeq 10^{-19}\ km^{-1}$$

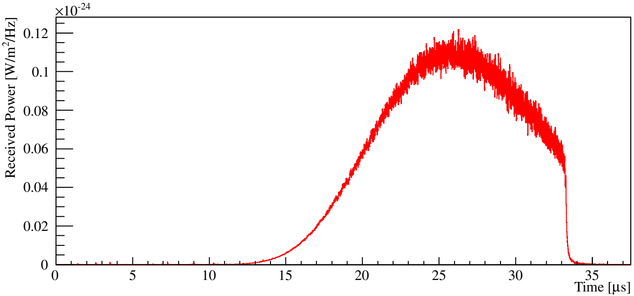
$\Rightarrow$ At GHz frequencies, the absorption is found to be negligible.

- Monte Carlo sampling of the observable spectral intensity in r and ϕ
- Spectral intensity as a function of time expected at different distances from the shower core at ground level, for a vertical shower with energy $10^{17.5}$ eV.



⇒ Close to the shower core, values are in the order or below from the ones measured of other sources of microwave radiations, such as geomagnetic effects.

Spectral intensity as a function of time expected at 10 km from the shower core at ground level, for a vertical shower with energy $10^{17.5}$ eV.



⇒Values obtained at 10 km from the shower axis are a factor 25 less than expected when scaling beam measurements to air showers in reference [1].

⇒ Good sensitivity microwave detectors should detect the expected MBR intensity

Conlusion

- Detailed analytical calculation of the MBR spectral intensity has been undertaken
- Numerical solving of Boltzmann equation considering ionization, attachment and excitation of secondary electrons describe their time evolution in the plasma
- Calculated spectral intensity at ground gives a factor 25 lower than expected in [1]
- Still achievable detection with good sensitivity sensors
- Plasma dispersion effects are still to include in the calculation

References

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