PARTICLE ACCELERATION BY DIRECT ELECTRIC FIELDS IN AN ACTIVE REGION MODELLED BY A CELLULAR AUTOMATON

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1- CA model

2- Acceleration model

3- particle energy distributions

4- X-ray and gamma ray fluxes

Introduction

- We use a cellular automaton (CA) model to mimic the energy release process (Vlahos et al, 1995 ...)

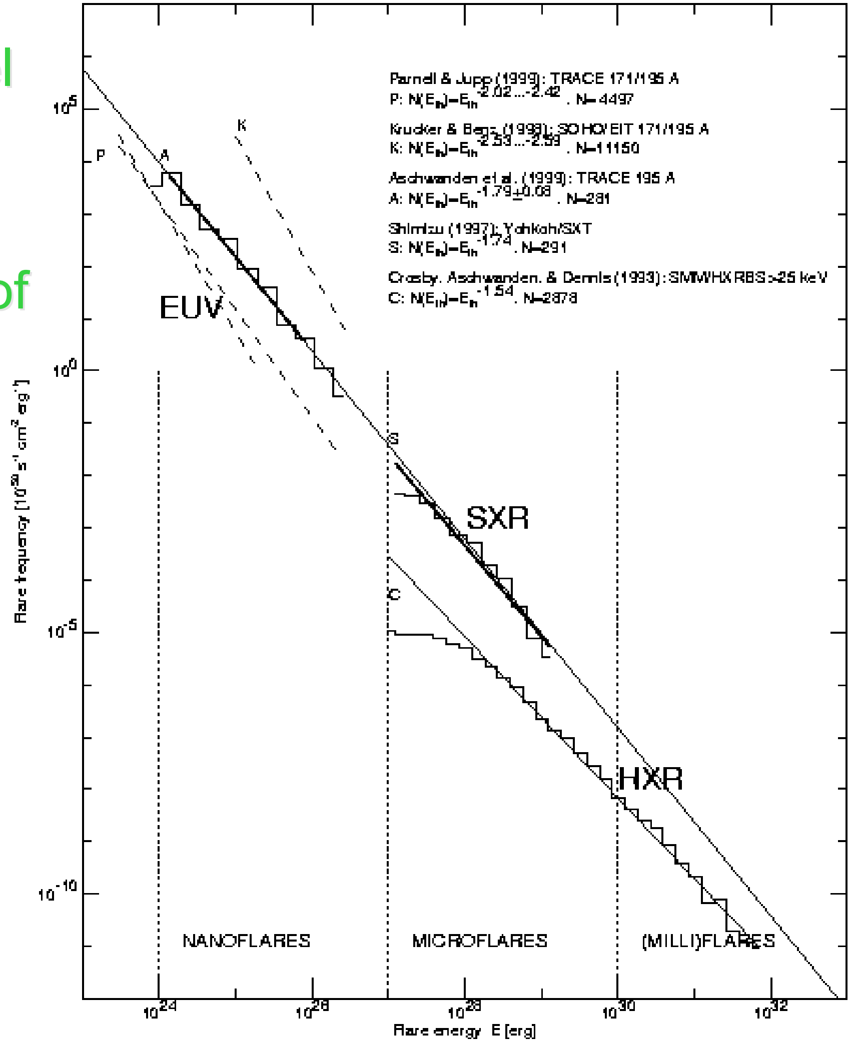
  CA can reproduce statistical properties of solar flares (i.e. for the all sun)

- Frequency distributions of, e.g., flares energy power law

  Hudson, 1991   Crosby et al, 1993 …

   no characteristic scale

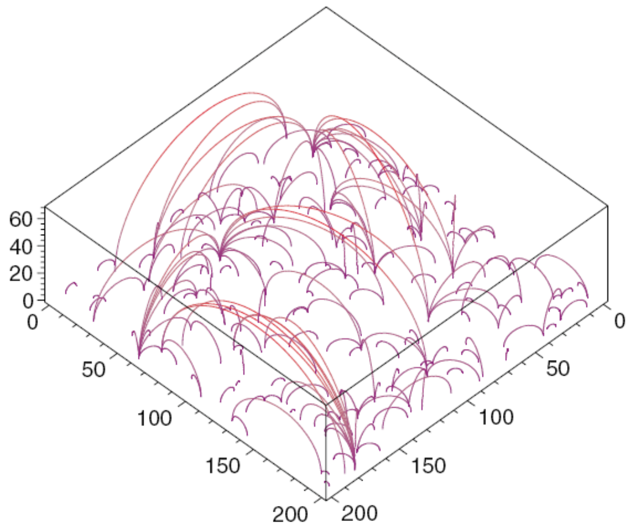
   Simple rules can model the system



Aschwanden et al,2000

Introduction

- Can we use a CA model to mimic the energy release process in an active region ?
- Current sheet can have a fractal structure (Yankov, 1996)
- Extrapolation of magnetic field shows the complexity of an active region

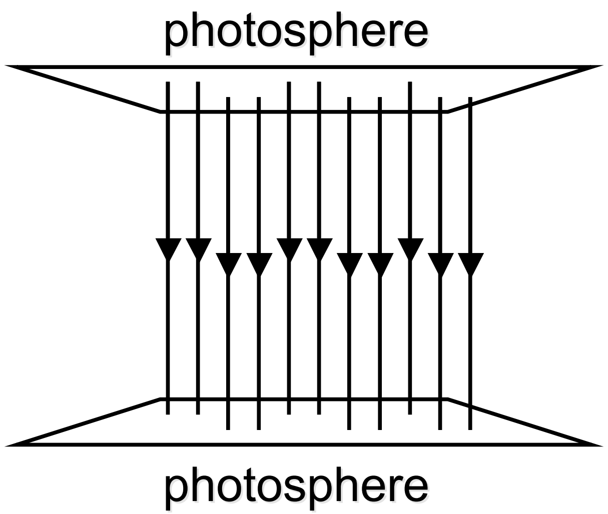


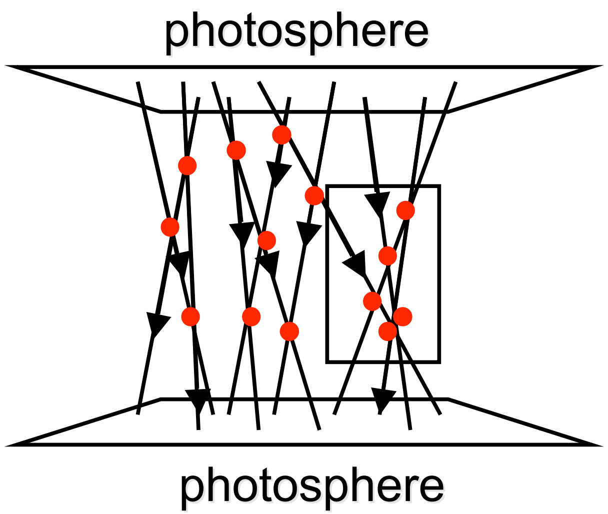
Hughes et al, 2003

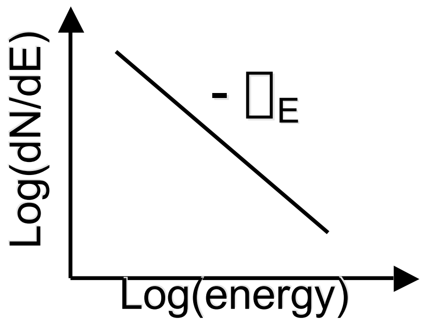
- Hughes et al, 2003: solar flare can be reproduced by cascades of reconnecting magnetic loops which evolve in space and time in a SOC state

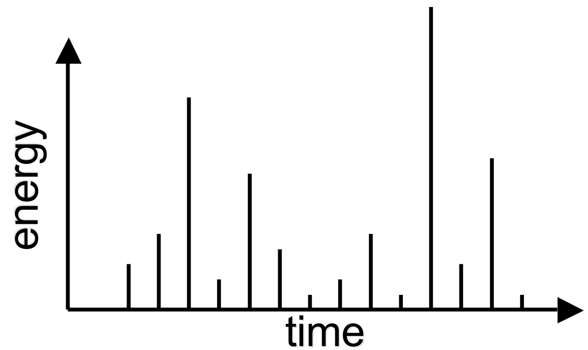
Introduction

- Random foot-points motion => buildup of magnetic discontinuities in the corona









CA model

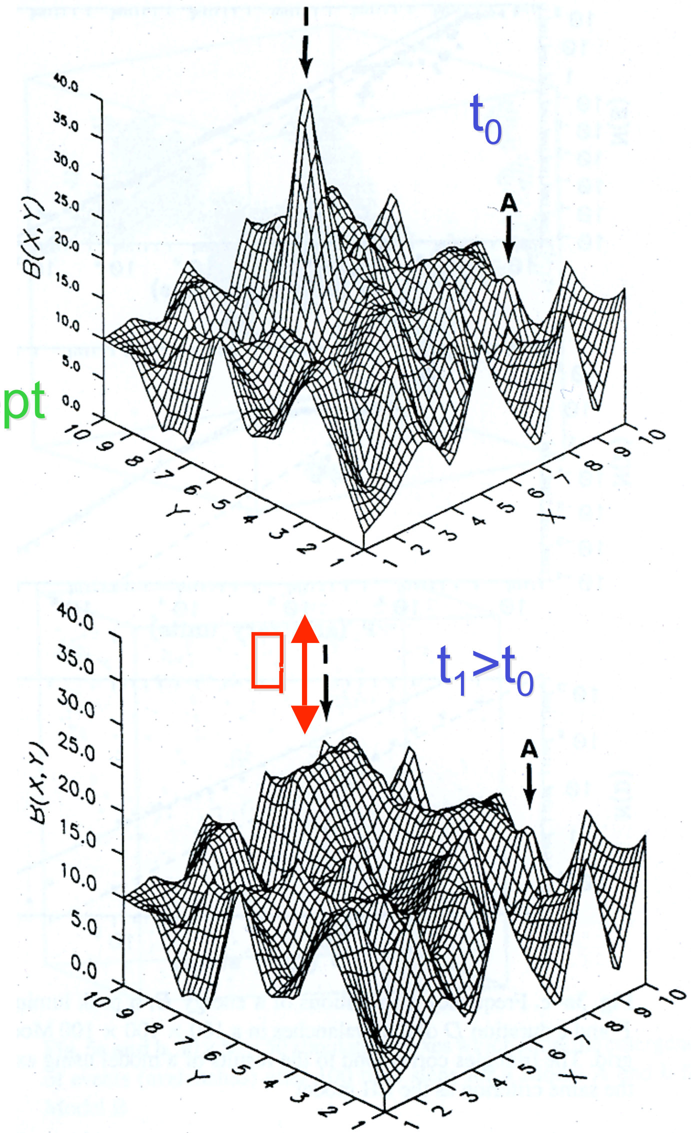
- Is the evolution of magnetic discontinuities based on Self Organized Criticality system ?
  □ assumption (Lu et Hamilton, 1993; Vlahos, 1995; McIntosh et al, 1992 …)
- We use a CA model based on the SOC concept (Vlahos et al, 1995; Georgoulis et al, 1998)
- Basic rules:

  -3D cubic grid: $B_i=B(x,y,z)$ at each grid point

  - At each time step $B_i(t+1)=B_i(t)+□B_i(t)$ and $prob(□B_i)=□B_i^{-5/3}$

  - if (Bi-1/6∑Bj)>Bcr □ $□_i$~B_i^2

  Curvature of B at the point i = dB_i



CA model

- Magnetic field evolution:

$$B_i(t+1) = B_i(t) - \frac{6}{7} dB_i(t)$$

$$B_{i+j}(t+1) = B_{i+j}(t) + \frac{1}{7} dB_{i+j}(t)$$

Isliker et al, 1998
- Link to diffusion

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \nabla^2 B$$

$$prob(\Delta B_i(t)) = (\Delta B_i(t))^{-5/3}$$

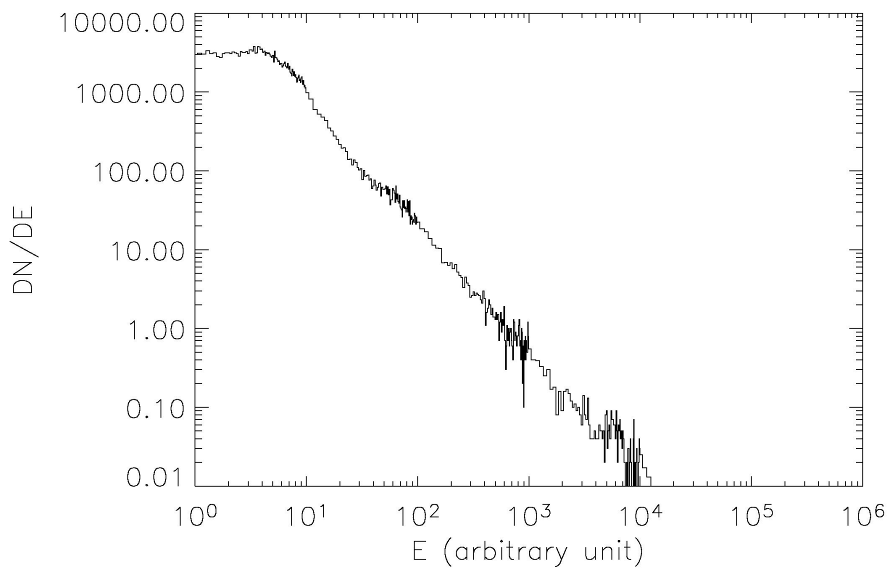
to mimic the turbulent motion of the magnetic loops foot points

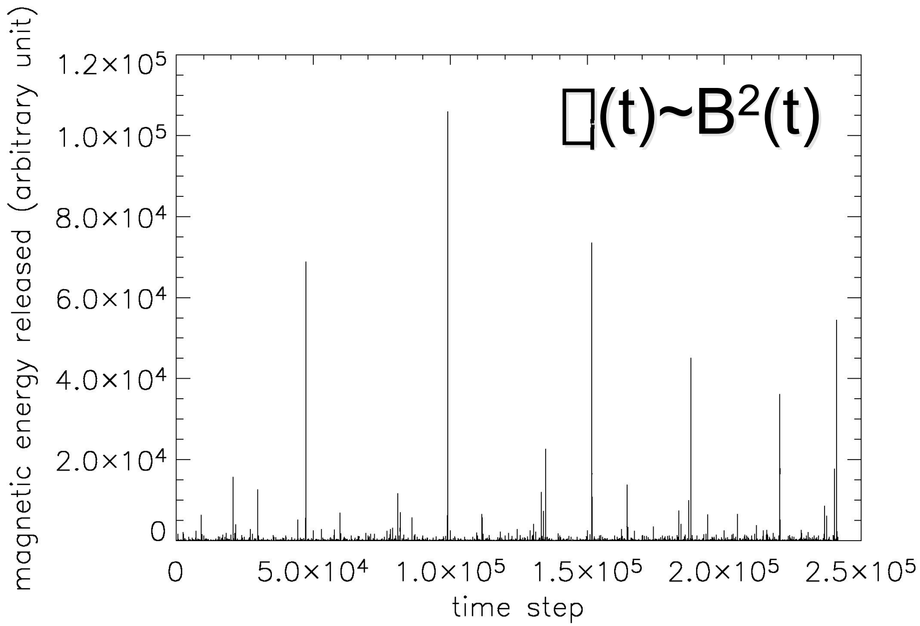
Espagnet et al,1993

CA model

- ⇨ □(t)~B^2(t) Energy released time series

- □ power law distribution: $□_E$~ -1.6





Acceleration model

- We have one model of energy release process in an active region
- We want to accelerate particle

   each magnetic energy release process RCS (reconnecting current sheet; observed in tokamak (Crocker at al, 2003) and in laboratory)

- We have to make the link between the energy release process and the acceleration process.

One of the first step in this sense Anastasiadis et al, 2004

Acceleration model

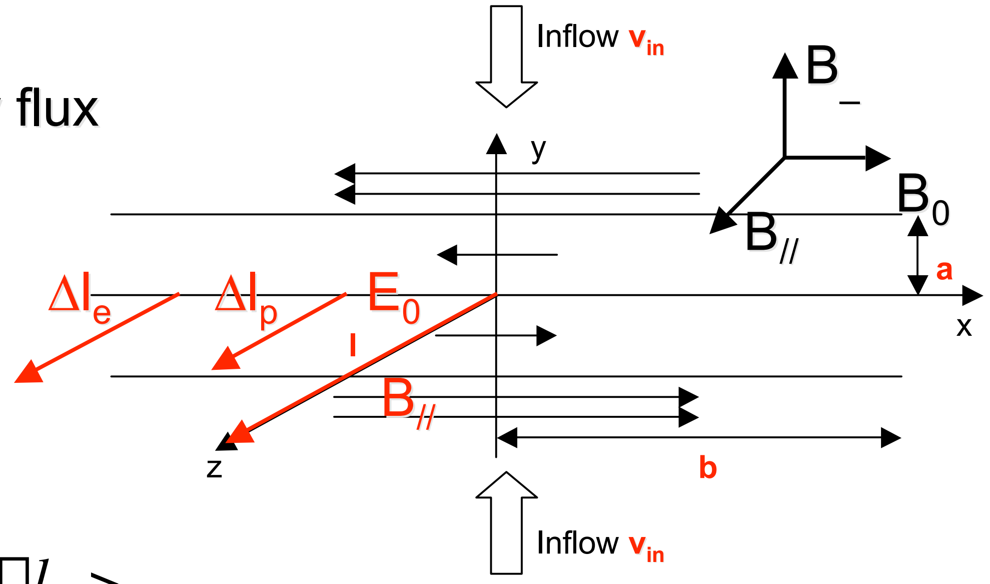
- We equate the magnetic energy flux

$$P = \frac{1}{\square} v_{in} B_0^2 bl$$

- to the particle energy gain per unit time

$$P = \dot{N}_e e E_0 < \Delta l_e >_{n_e} + \dot{N}_P e E_0 < \Delta l_p >_{n_p}$$

with $\dot{N} = 4lbv_{in}n$



- $\Longrightarrow$ $$E_0 = \frac{B_0^2}{4\square e(\langle \Delta l_e \rangle_{n_e} n_e + \langle \Delta l_p \rangle_{n_p} n_p)}$$

Acceleration model

- ⇨ Electric field ⇨ Particle energy gain (electron, proton and heavy ions)

$\Box = \pm\Box\, eE_0 < \Box l >$ We use a simple approach of the acceleration by direct electric field □=random([0,1]) efficiency of the acceleration

- $$\Box_e = \pm\Box \frac{B_0^2}{4\Box(n_e + \Box n_p)}$$

$$\Box_p = \pm\Box\Box \frac{B_0^2}{4\Box(n_e + \Box n_p)}$$

$$\Box_i = \pm\Box Z \Box_i \frac{B_0^2}{4\Box(n_e + \Box n_p)}$$

CA Model

OR :X-CA (hybrid simulation)

OR: MHD simulation ; extrapolation

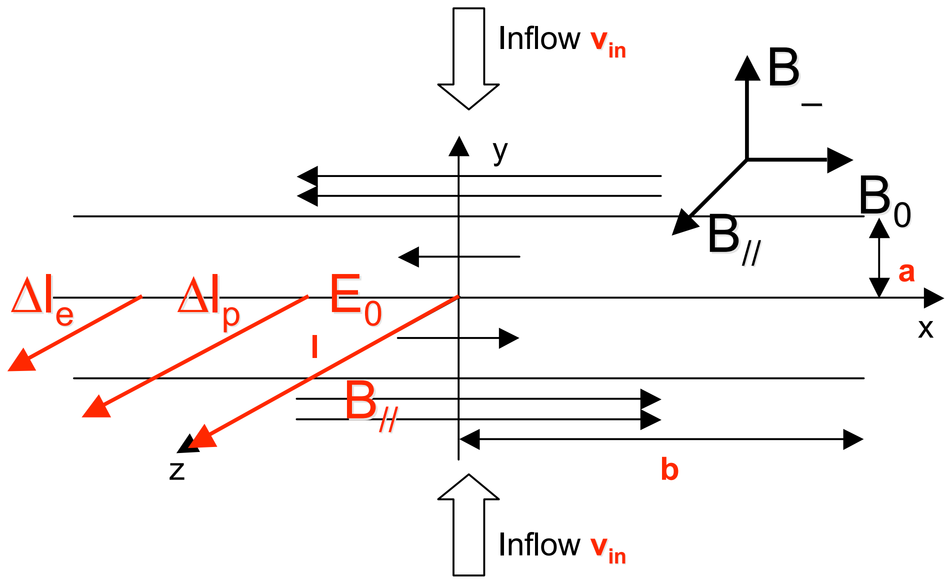
$$\Box = \frac{\langle \Box l_p \rangle_{n_p}}{\langle \Box l_e \rangle_{n_e}}$$

$$\Box_i = \frac{\langle \Box l_i \rangle_{n_i}}{\langle \Box l_e \rangle_{n_e}}$$

RCS (direct electric field)

Acceleration model

- We use 3 assumptions for $B_{//}$



- $B_{//} = 0$ (Speiser, 1965)

$$\Rightarrow \square = 2mc^2 \left(\frac{E_0}{B_\square} \right)^2$$

$$\Rightarrow \square = \frac{m_p}{m_e}$$

- Protons gain more energy than electrons

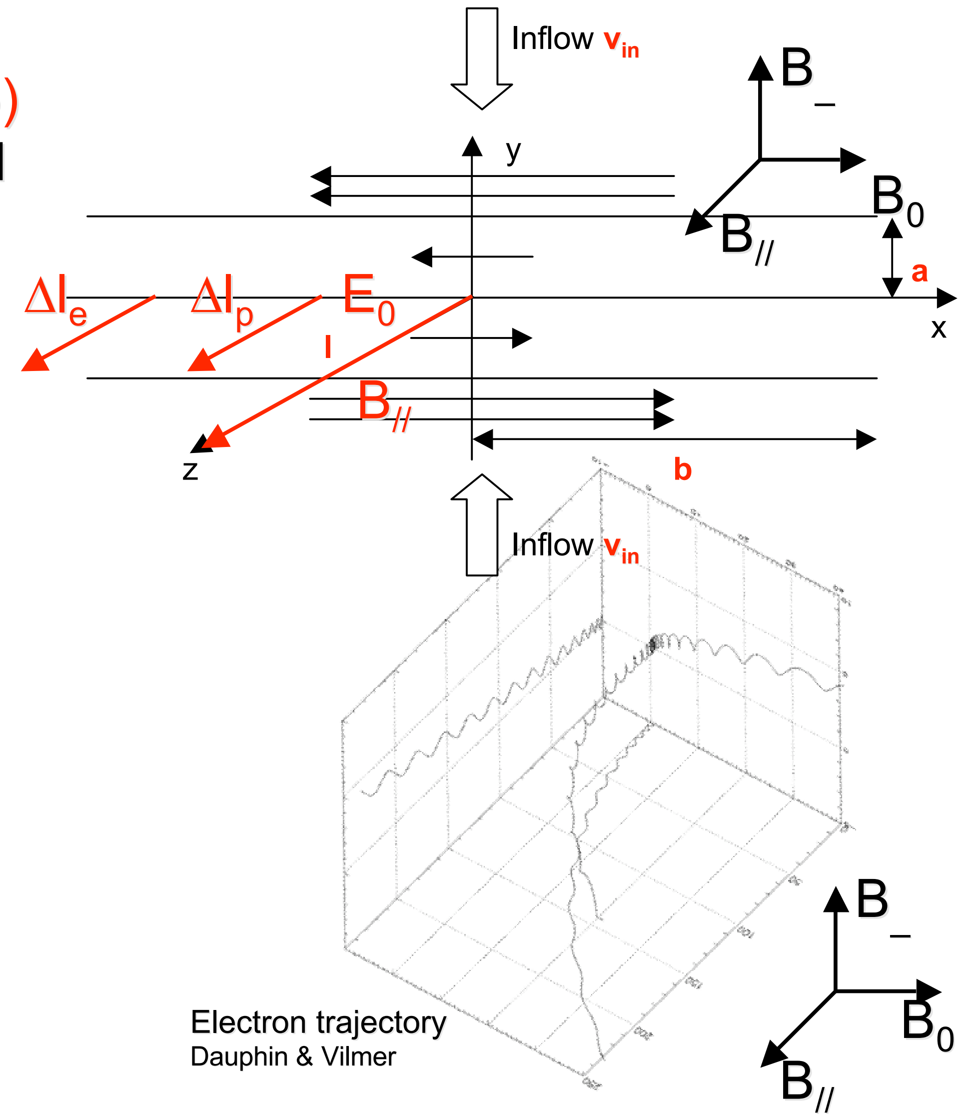
Acceleration model

- $B_{//} > B_{mag}(e^{-},\text{ions})$ (Litvinenko, 1996)
  electrons and ions are magnetized
  => follow the magnetic field lines

$$B_{mag(e,p)} = \sqrt{\frac{mc^2 E_0 B_0}{eaB_{\perp}}}$$

$$\Rightarrow \square = \frac{B_{//}}{B_{\perp}} eaE_0 \Rightarrow \square = \square_i = 1$$

- Same energy gain for all particle



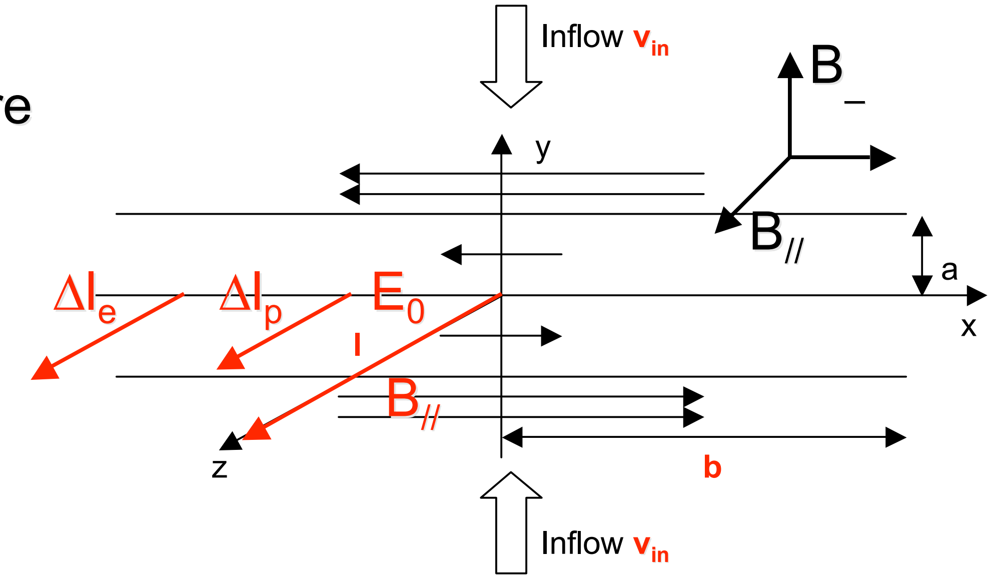
Electron trajectory
Dauphin & Vilmer

Acceleration model

- $B_{//} > B_{mag}(e^-)$ only the electrons are magnetized

$$\Rightarrow \quad \square = \sqrt{\frac{m_e}{m_p}}$$

$$\square_i = \sqrt{\frac{Z m_e}{m_i}}$$

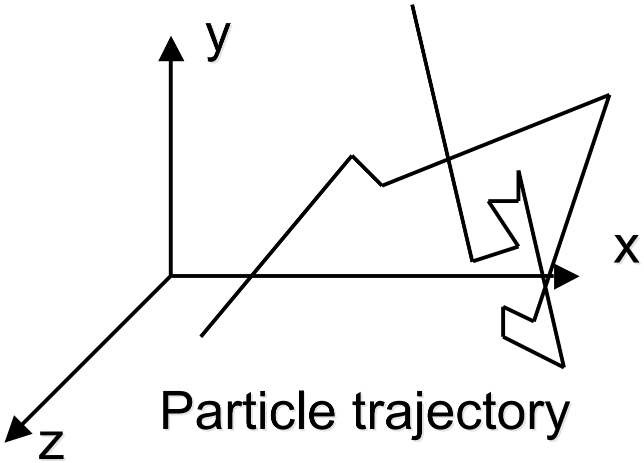


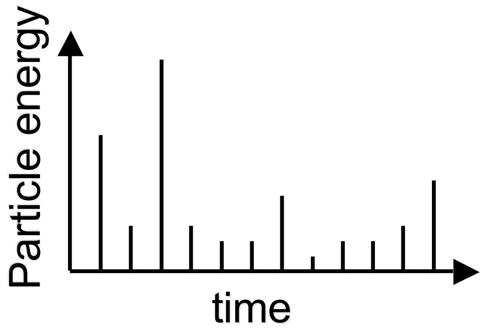
- We have the particle energy gain for 3 different RCS configurations
  For each particle (e^- or ions) we select a value of $\square$ and we select a value of B^2_{free} from the energy release time series

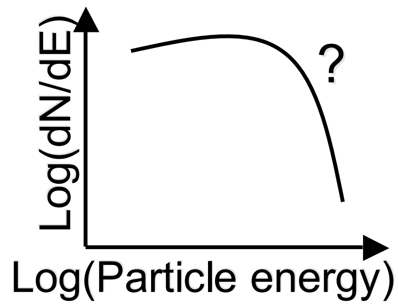
$$\square_e = \pm \square \frac{B_0^2}{4\square(n_e + \square n_p)} \qquad \square_p = \pm \square\square \frac{B_0^2}{4\square(n_e + \square n_p)} \qquad \square_i = \pm \square Z \square_i \frac{B_0^2}{4\square(n_e + \square n_p)}$$

Particle distribution

- Equivalent to a Levy Walk powerful events govern the particle trajectory







- We calculate the particle energy distribution for 10^6 particles from a maxwellian distribution ($T=10^6$ K)

- For electrons, protons, and heavy ions

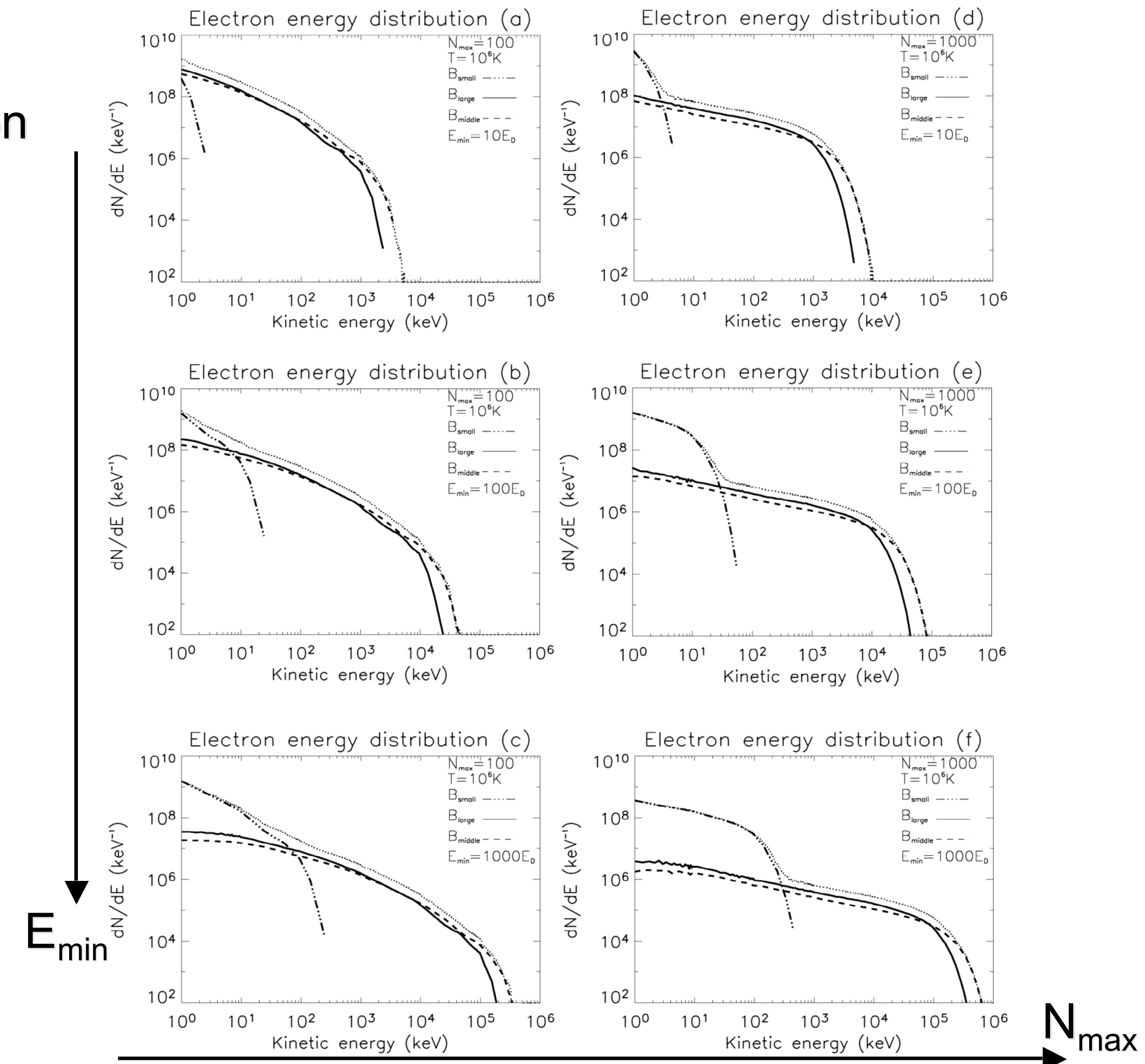
- For the 3 different configuration of RCS

We normalize the electric field in the case $B_{//}$ large to the Dreicer electric field.

=> free parameter

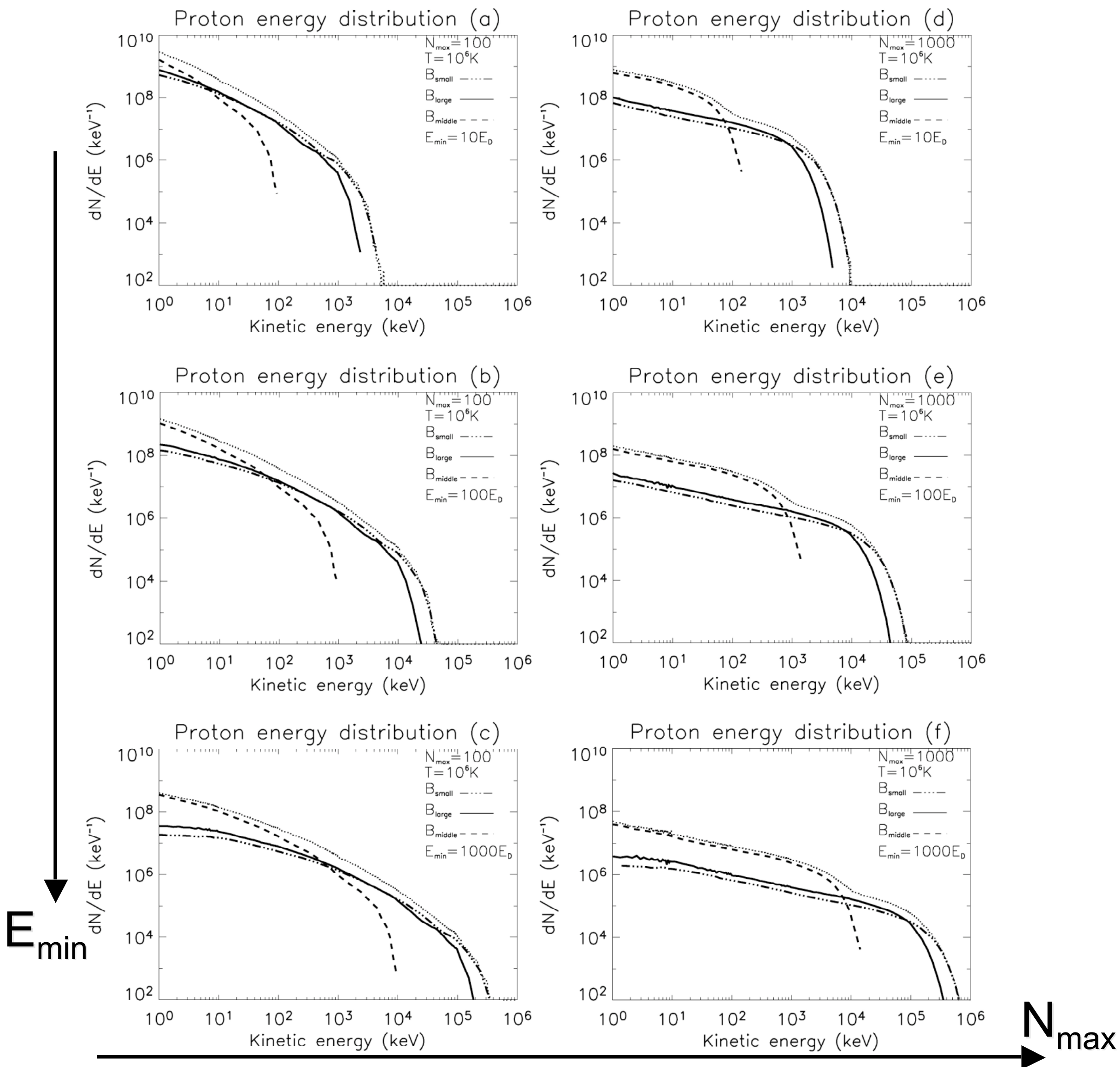
Particle distribution

- Example for electron



Particle distribution

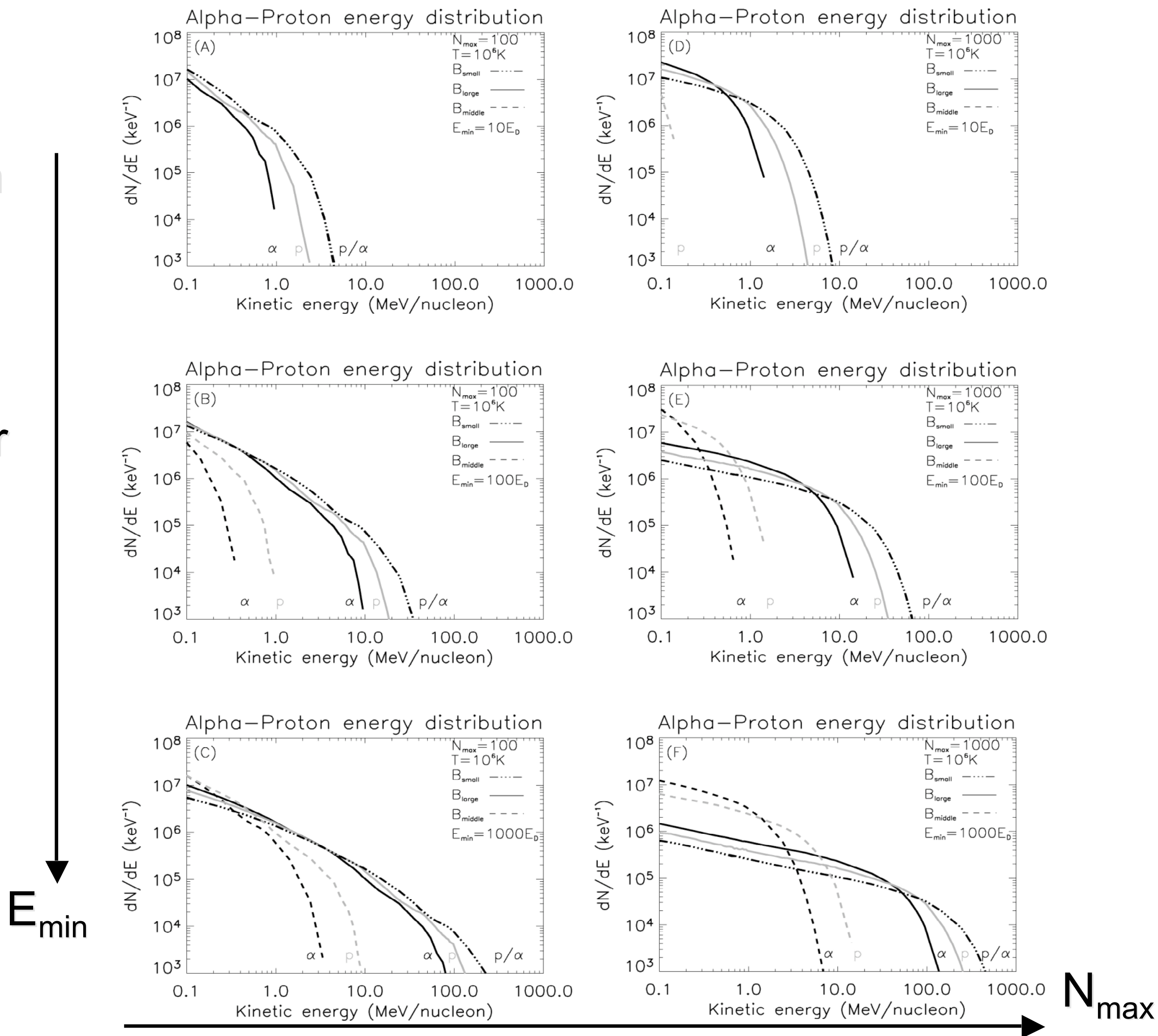
- Example for proton



Particle distribution

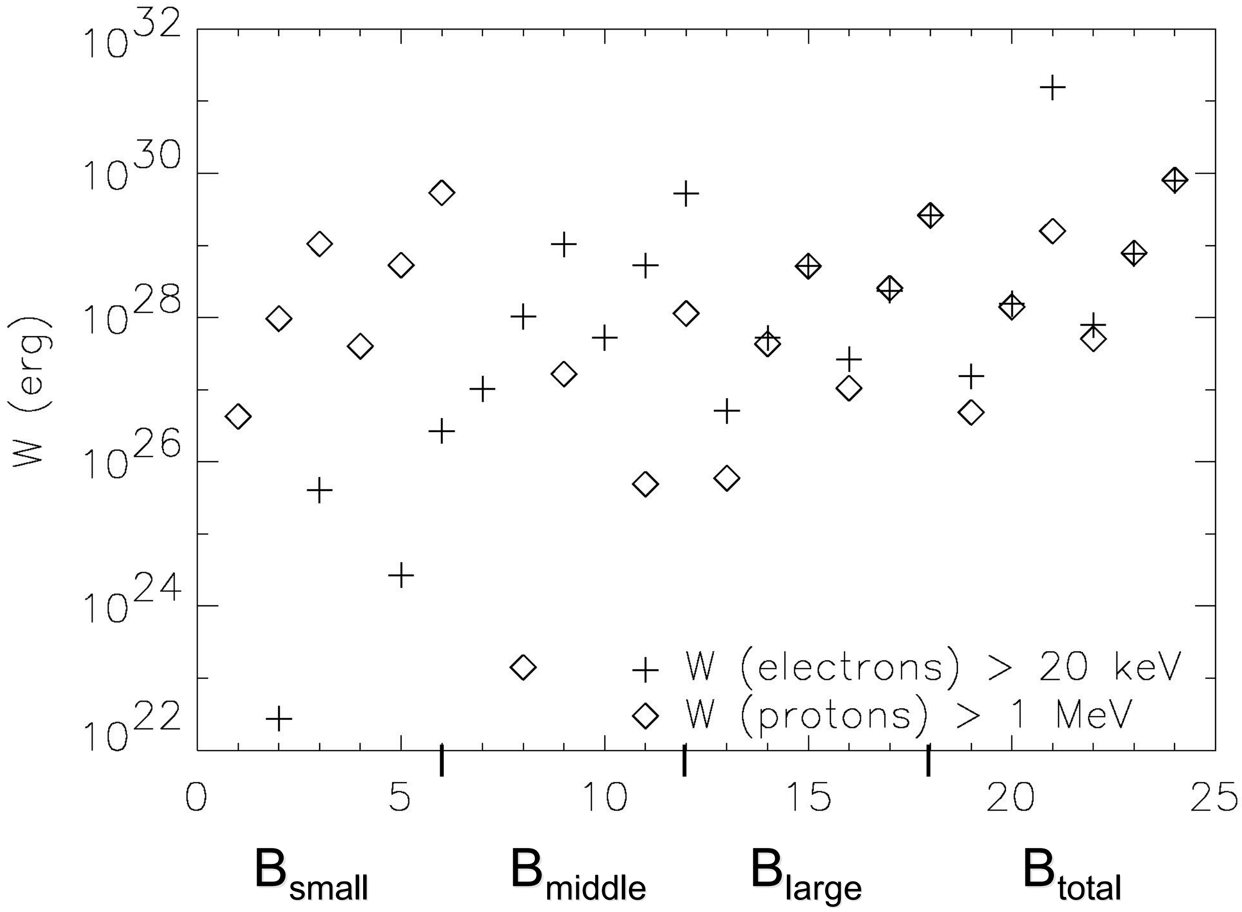
- Example of alpha energy distribution

  No difference between the two spectra in energy/nucleon for the case B_{small}



Energy contained

- Energy contained in accelerated particles (for 1 arcsec³)



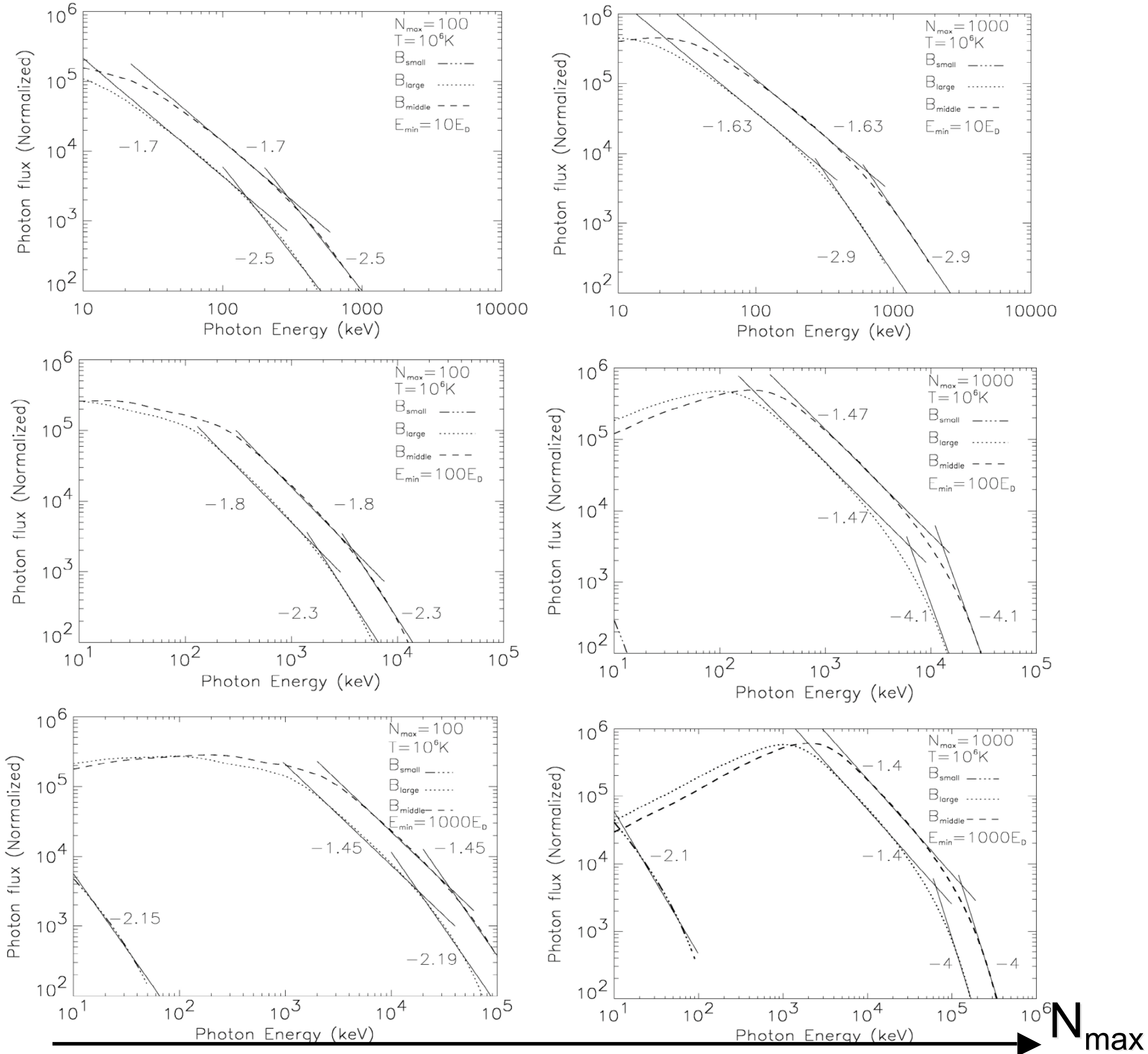
X-Ray flux

- Thick target approach
- Cases observed:

  - B_{small}, $E_{min}=1000E_D$

  - $E_{min}=10ED$

E_{min}



Gamma Ray flux

- We compute the gamma ray ratio calculated in the thick target approximation

^{12}C+p, ^{12}C+□, ^{16}O+p, ^{16}O+□ } □ 4.438 MeV

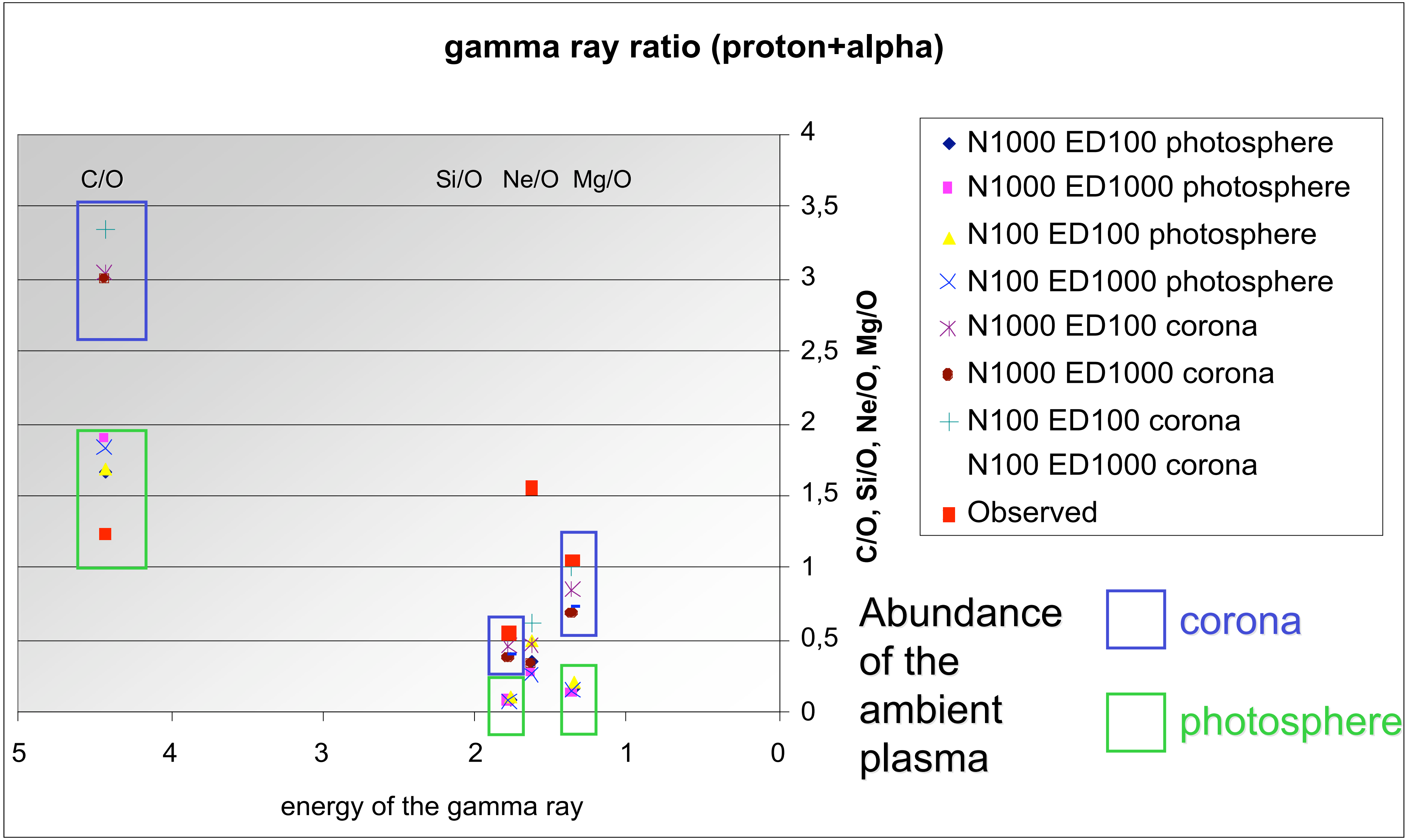
^{16}O+p, ^{16}O+□ } □ 6.129 MeV

^{20}Ne+p, ^{20}Ne+□ } □ 1.634 MeV

^{24}Mg+p, ^{24}Mg+□ } □ 1.364 MeV

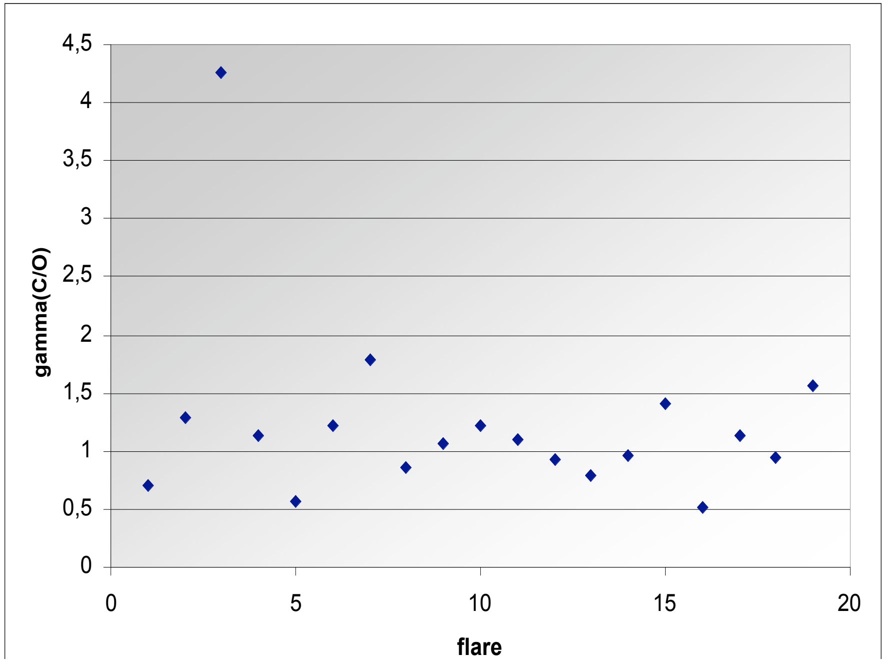
^{28}Si+p, ^{28}Si+□ } □ 1.779 MeV

Gamma Ray flux

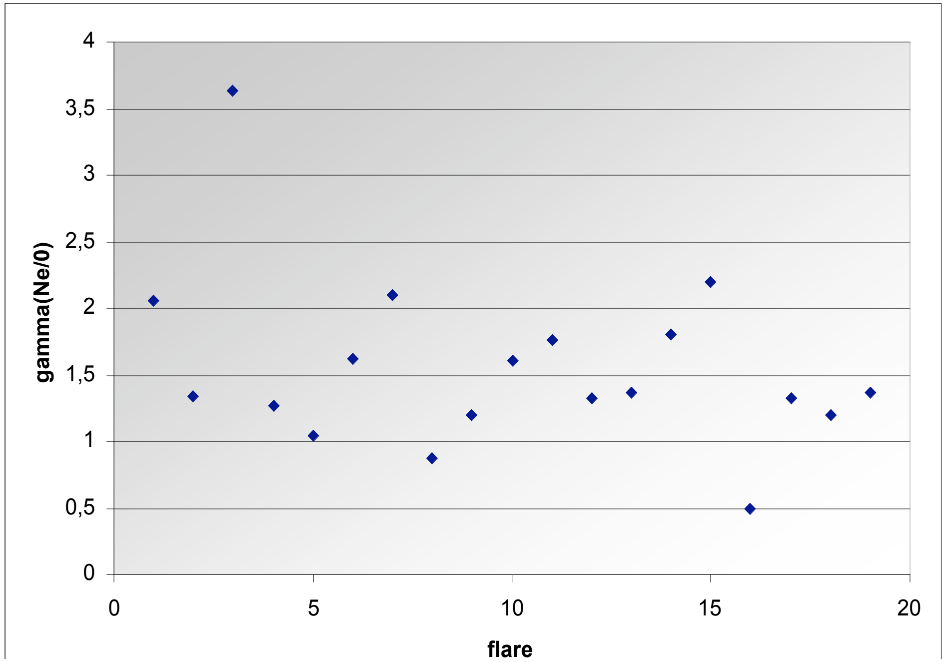


Gamma Ray flux

- Observations from Share and Murphy, 1995



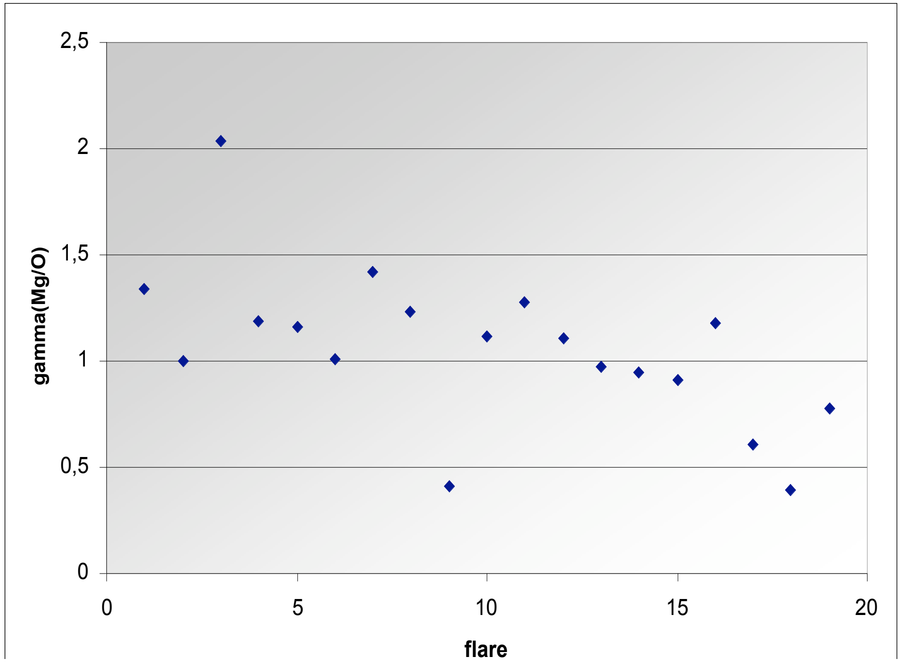
Average=1.06



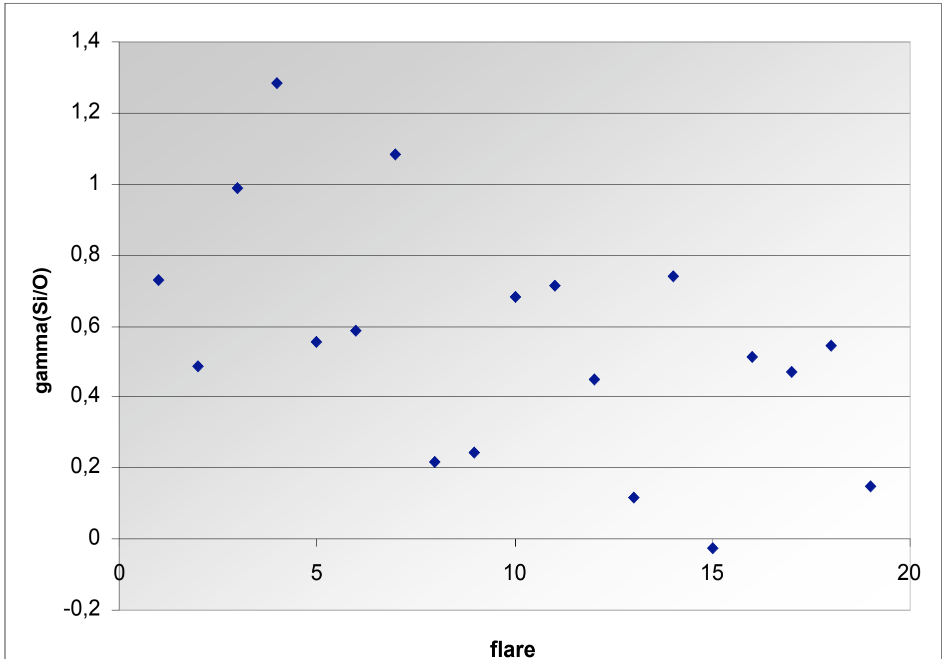
Average=1.44

Gamma Ray flux

- Observations from Share and Murphy, 1995



Average=1



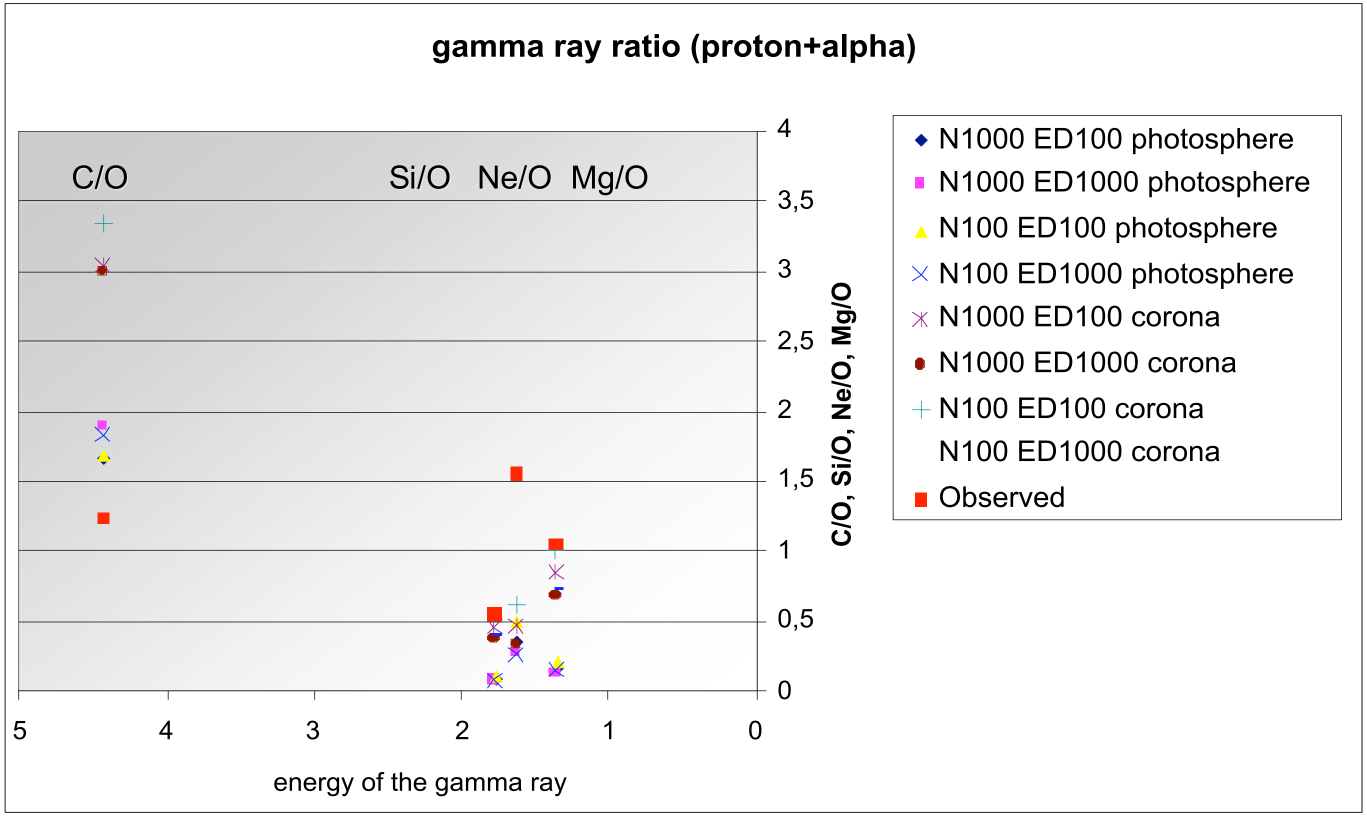
Average=0.5

Gamma Ray flux

- Si/O and Mg/O correspond to the coronal abundance

  C/O in agreement with the ratio deduced by using a photospheric abundance

  Problem with Ne/O



Conclusions

- We investigate particle acceleration due to interaction with many RCS. The magnetic energy release distribution is given by a power law
- - particle energy distributions wander from a power law with the increase of the interaction number and strongly depend on the considered RCS configuration
- Spectral index of the particle distribution is function of the considered energy range
- This implies different X-ray spectra and gamma ray line fluence ratio; in most cases X-ray spectra are too flat compared to observations. This is mainly due to the spectral index of the magnetic energy released distribution which is -1.6.

   Observed gamma ray lines fluence ratio can be reproduced except for Neon

Conclusions

- => This implies different X-ray spectra and gamma ray line fluence ratio

Energy contained in electron and proton strongly depends on the RCS configuration -> see observations

With a volume of 10^2-10^3 arcsec^3, it is possible to obtain enough energy in electron and proton to reproduce most of the observations