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High Energy Particle Transport in a Solar Magnetised Medium with Geant4

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INTRODUCTION

- Solar flares are intense and transient events taking place at active regions in the solar atmosphere and involve the energy release of 10²⁷ to 10³² erg in tens of seconds to tens of minutes.
- Measurements at Earth had already shown that energetic ions could attain energies > 10 GeV. (Meyer, Parker, and Simpson, 1956; Rishbeth, Shea, and Smart, 2009)
- Observations of ~100 MeV γ-rays→ ions may interact with solar atmosphere
 (Forrest et al., 1985; Kanbach et al., 1993; Ackermann et al., 2014)



10¹⁰

10

10⁰

10-5

10⁻¹⁰

Flux (photons cm⁻² s⁻¹ keV⁻¹)

Thermal

electrons

SOFT X-RAYS

10¹

Nonthermal electrons High-energetic High-energetic Pions electrons Nonthermal electrons Nonthermal electrons Nonthilation line Neutron Capture line Deexcitation lines Pion Decay

π

10⁶

10⁵

- Bremsstrahlung
- Pair Production

• Ionization



 10^{3}

Photon energy [keV]

511 keV

HARD X-RAYS

10²

2.2 MeV

GAMMA-RAYS

 10^{4}



INTRODUCTION MONTE CARLO CODES

- Monte Carlo codes as a tool for these kind of problems.
- Deal with arbitrary geometries, chemical abundances and reactions from known cross sections.
- > Well validated models.
- Kotoku et al. 2007 → electron transport and resulting gamma-ray spectra.
- · Tang & Smith 2010 → Ion transport using Geant4.
- Tusnsky et al. 2019 & McKinnon et al.
 2020 → Ion transport using Fluka.
- Abdo et al. 2011 → Gamma radiation from quiet sun.





METHODOLOGY

Geant4

• Geant4 (GEometry ANd Tracking)(Agostinelli et al., 2003) are Monte Carlo packages wide used in high energy experimental physics to simulate the passage of particles through matter.

• Both, cover a wide range of applications as proton or electron accelerator projects calorimeters, dosimetry, cosmic rays, radiotherapy, physics of neutrinos, etc



METHODOLOGY SOLAR FLARE MODEL

- Asplund Abundances (Asplund, 2009).
- Thick target → column depth to stop accelerated primary particles.
- Neutral target.
- Secondaries crossing from the chromosphere/photosphere to the corona are scored.



METHODOLOGY Solar flare model

Beam of primary particles:

- Protons or electrons
- Angular distribution:
 - Isotropic
 - Isotropic Downward
- Energy Distribution:
 - Monoenergetic
 - Power-law



Newton-Lorentz formalism



Newton-Lorentz formalism

METHODOLOGY MAGNETIC FIELD









The GC description consider the effective movement of the particle along magnetic field lines with magnetic moment μ constant.

Guiding Center approach



Guiding Center approach

$$\begin{aligned} \frac{d\mathbf{R}}{dt} &= \frac{\gamma m v^2}{2qB^2} \left(1 + \frac{v_{\parallel}^2}{v^2} \right) \mathbf{\hat{b}} \times \nabla B(\mathbf{R}) + v_{\parallel} \mathbf{\hat{b}} \\ \frac{dv_{\parallel}}{dt} &= -\frac{\mu}{\gamma^2 m} \mathbf{\hat{b}} \cdot \nabla B(\mathbf{R}) \,. \end{aligned}$$



Guiding Center Implementation in Geant4

$$\begin{aligned} \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} &= \frac{\mathrm{d}p_{\parallel}}{\mathrm{d}t}\hat{\mathbf{b}} + p_{\parallel}\frac{\mathrm{d}\hat{\mathbf{b}}}{\mathrm{d}t} + \frac{\mathrm{d}p_{\perp}}{\mathrm{d}t}\left(\delta\hat{\boldsymbol{\xi}} + \epsilon\hat{\boldsymbol{\zeta}}\right) + p_{\perp}\delta\left(\mathbf{v}_{GC}.\nabla\right)\hat{\boldsymbol{\xi}} + \epsilon\left(\mathbf{v}_{GC}.\nabla\right)\hat{\boldsymbol{\zeta}} \\ \\ \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} &= \frac{\gamma m v^2}{2qB^2}\left(1 + \frac{\left(\mathbf{v}.\hat{\mathbf{b}}\right)^2}{v^2}\right)\hat{\mathbf{b}} \times \nabla B(\mathbf{r}) + (\mathbf{v}.\hat{\mathbf{b}})\hat{\mathbf{b}} \end{aligned}$$

GC Equations of Motion implemented in Geant4





-0.4

0

1000 2000

3000

4000

x [km]

5000 6000 7000 8000

RESULTS Dipole Magnetic Field

- GC

4000 6000 8000

N

GC

4000 6000 8000

0 2000

x [km]

-1.5 -1.0 -0.5 0.0 0.5 1.0

y [km]

2000

0

x [km]

Figure 16 – Trajectories of a primary proton with initial kinetic energy $E_{k0} = 1.0$ GeV in a dipole magnetic field obtained in simulations with the GC and NL approaches. Left panels: initial pitch angle $\theta = 15^{\circ}$; Right panels: initial pitch angle $\theta = 35^{\circ}$.

-3.0

-8000 -6000 -4000 -2000





Figure 17 – Comparison between the energy losses of a primary proton in a dipole magnetic field obtained in simulations with the GC and NL approaches. The plots are for an initial pitch angle $\theta = 15^{\circ}$ and initial kinetic energies $E_{k0} = 0.5$ GeV (A), $E_{k0} = 1.0$ GeV (B) and $E_{k0} = 5.0$ GeV (C).

RESULTS

Dipole Magnetic Field



Single Proton Dipole Magnetic Field

RESULTS Dipole Magnetic Field

E_{k0} (GeV)	θ (deg)	GC(s)	NL(s)
0.5	15	4.4	206.4
1.0	15	4.2	2258.7
5.0	15	4.9	5364.2
1.0	35	2.8	102.5 †

Table 7 – Runtimes for simulations of a primary proton in a dipole magnetic field with the GC and NL approaches. † With stopping condition (see the text).



Particle	Method	$ar{n}$	σ
<i>e</i> ⁻	GC	335698	2717
	NL	342598	7892
e^+	GC	519	9
	NL	529	13
π^0	GC	124	8
	NL	132	17
π^{-}	GC	6	3
	NL	7	2
π^+	GC	331	8
	NL	320	7
γ	GC	3053	36
	NL	3149	152
n	GC	452	6
	NL	435	18

RESULTS Secondary Production

- Monoenergetic protons 1 GeV
- 5 runs of 1000 primary each
- \cdot Released inside the loss cone
- Detectors set at chromospheric/photospheric region

Runtimes:
 NL ~190 hours ~ 8 days
 GC ~14 minutes



RESULTS Gamma-ray spectra



Figure 28 – Gamma-ray spectra from primary protons in a dipole magnetic field obtained in simulations with the GC approach. The primary protons are released from the top of the reference magnetic field line and assumed to have an isotropic angular distribution and a power-law energy distribution with spectral indexes $\delta = 2$ (left panel) and $\delta = 3$ (right panel) in the range from 1.0 MeV to 1.0 GeV. The panels depict the total spectrum as well as the contributions from e+ annihilation, neutron-capture, proton inelastic processes, e± bremsstrahlung and $\pi 0$ decay.



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RESULTS Double Dipole

 $\vec{\mu} = \mu \hat{\mathbf{x}}$ $B_f = 1000 \text{ G}$ $d_x = 500 \text{ km}$ $d_z = 0.012 \text{ Rs}$ $R_f = 0.010 \text{ Rs}$



RESULTS Double Dipole





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(c)

(d)



CONCLUSIONS Conclusions

- We have implemented a GC description of charged particle transport in magnetic fields within Geant4:
 - Single particles modelled using the GC equations of motion follow trajectories that are the same, to within a gyroradius.
 - > They follow field lines, drifting slowly across them at the correct rate.
 - > In a denser medium they slow down at the correct rate and stop at the correct depth.
 - Calculating energy and angle distributions of secondaries would be computational unfeasible in the NL case for a huge number of primaries.
- The GC run times are two to five orders of magnitude shorter than for the NL computation, depending on the energies of the primaries.
- The model it is interesting for other areas of knowledgment in Astrophysics to speed up simulations involving magnetic fields.









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For more information, paper submitted on A&A :

'Modelling Magnetised Medium Particle Transport in the Guiding Centre Limit with GEANT4'

The code is public and avaiable on:

https://github.com/guigue/Geant4_Codes_for_Solar_Simulations/tree/master









Dipole Aproximation

$$\begin{split} \mathbf{B}(\mathbf{r}) &= \frac{3[\vec{\mu} \cdot (\mathbf{r} - \mathbf{r_d})](\mathbf{r} - \mathbf{r_d}) - |\mathbf{r} - \mathbf{r_d}|^2 \vec{\mu}}{|\mathbf{r} - \mathbf{r_d}|^5} \\ B_x &= \mu \frac{2x^2 - y^2 - (z + d_z)^2}{[x^2 + y^2 + (z + d_z)^2]^{5/2}} \\ B_y &= \mu \frac{3xy}{[x^2 + y^2 + (z + d_z)^2]^{5/2}} \\ B_z &= \mu \frac{3x(z + d_z)}{[x^2 + y^2 + (z + d_z)^2]^{5/2}} \\ \mu &= B_f \frac{(R_f^2 + d_z^2)^{5/2}}{\sqrt{4R_f^4 + 5R_f^2 d_z^2 + d_z^4}} \end{split}$$









Figure 14 – Trajectories of a primary proton in a uniform magnetic field obtained with the GC and NL approaches. Left panels: initial kinetic energy $E_{k0} = 0.25$ GeV and initial pitch angles $\theta = 15^{\circ}$, $\theta = 35^{\circ}$ and $\theta = 80^{\circ}$; Right panels: initial pitch angle $\theta = 35^{\circ}$ and initial kinetic energies $E_{k0} = 0.5$ GeV, $E_{k0} = 1.0$ GeV and $E_{k0} = 5.0$ GeV.

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RESULTS Uniform Magnetic Field

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Fig. 3: Comparison between the energy losses of a primary proton in a uniform magnetic field obtained in simulations with the GC and NL approaches. Left panel: initial kinetic energy $E_{k0} = 0.25$ GeV and initial pitch angles $\theta = 15^{\circ}$ (A), $\theta = 35^{\circ}$ (B) and $\theta = 80^{\circ}$ (C); Right panel: initial pitch angle $\theta = 35^{\circ}$ and initial kinetic energies $E_{k0} = 0.5$ GeV (A), $E_{k0} = 1.0$ GeV (B) and $E_{k0} = 5.0$ GeV (C).



Single Proton Uniform Magnetic Field

RESULTS Uniform Magnetic Field

E_{k0} (GeV)	θ (deg)	GC(s)	NL (s)
0.25	15	3.0	19.3
0.25	35	2.8	27.6
0.25	80	3.5	20.9
0.50	35	2.5	84.6
1.00	35	3.5	188.0
5.00	35	8.7	3211.0

Table 6 – Runtimes for simulations of a primary proton in a uniform magnetic field with the GC and NL approaches.



RESULTS Uniform Magnetic Field



Figure 20 – Histograms for the stopping depth distributions (z) obtained in simulations with the NL (blue) and GC (red) approaches for 1000 primary electrons with initial kinetic energy $E_{k0} = 100$ MeV and initial pitch angle $\theta = 15^{\circ}$.



Guiding Center approach Geant4

One quite often sees the GC equations written only in terms of $p_{\|}$ because p_{\bot} doesn't matter for the motion of the particle.

In Geant4 we need to follow the evolution of both components of p explicitly because they are needed as inputs to the particle's next nuclear interaction.



Guiding Center Implementation in Geant4

$$\hat{\xi} = \frac{1}{\sqrt{1 - b_z^2}} \hat{\mathbf{b}} \times \hat{\mathbf{z}} = \frac{1}{\sqrt{1 - b_z^2}} \begin{pmatrix} b_y \\ -b_x \\ 0 \end{pmatrix} \qquad \qquad \hat{\zeta} = \hat{\xi} \times \hat{\mathbf{b}} = \frac{1}{\sqrt{1 - b_z^2}} \begin{bmatrix} \hat{\mathbf{z}} - (\hat{\mathbf{b}} \cdot \hat{\mathbf{z}}) & \hat{\mathbf{b}} \end{bmatrix} = \frac{1}{\sqrt{1 - b_z^2}} \begin{pmatrix} -b_x b_z \\ -b_y b_z \\ 1 - b_z^2 \end{pmatrix}$$

$$\delta = \frac{1}{p_{\perp}} \mathbf{p}_{\perp} \cdot \hat{\boldsymbol{\xi}} = \frac{1}{p_{\perp}} \mathbf{p} \cdot \hat{\boldsymbol{\xi}} \qquad \epsilon = \frac{1}{p_{\perp}} \mathbf{p}_{\perp} \cdot \hat{\boldsymbol{\zeta}} = \frac{1}{p_{\perp}} \mathbf{p} \cdot \hat{\boldsymbol{\zeta}} \qquad \delta^2 + \epsilon^2 = 1$$

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \frac{\mathrm{d}p_{\parallel}}{\mathrm{d}t}\hat{\mathbf{b}} + p_{\parallel}\frac{\mathrm{d}\hat{\mathbf{b}}}{\mathrm{d}t} + \frac{\mathrm{d}p_{\perp}}{\mathrm{d}t}\left(\delta\hat{\boldsymbol{\xi}} + \epsilon\hat{\boldsymbol{\zeta}}\right) + p_{\perp}\delta\left(\mathbf{v}_{GC}.\nabla\right)\hat{\boldsymbol{\xi}} + \epsilon\left(\mathbf{v}_{GC}.\nabla\right)\hat{\boldsymbol{\zeta}}$$