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Self-consistent Modelling of Nuclear Processes in Solar Flares using FLUKA

Sérgio Szpigel[a,*], Alexander MacKinnon[b], Carlos Guillermo Giménez de Castro[a], Paulo José Aguiar Simões[a], Daneele Saraçol Tusnski[a]

a *Centro de Rádio-Astronomia e Astrofísica Mackenzie, Escola de Engenharia, Universidade Presbiteriana Mackenzie São Paulo, Brazil,*

b *School of Physics and Astronomy, University of Glasgow Glasgow, United Kingdom*

E-mail: szpigel@mackenzie.br, alexander.mackinnon@glasgow.ac.uk, guigue@craam.mackenzie.br, paulo@craam.mackenzie.br, danesaracol@gmail.com

We use the Monte Carlo particle physics code FLUKA to calculate γ-ray spectra expected from solar flare energetic ion distributions. The FLUKA code includes robust physics-based models for electromagnetic, hadronic, and nuclear interactions, sufficiently detailed for it to be a useful tool for calculating nuclear de-excitation, positron annihilation and neutron capture line fluxes and shapes, as well as ~GeV continuum radiation from pion decay products. We show γ-ray model spectra which exhibit all the typical structures of γ-ray spectra observed in solar flares. From these model spectra we build templates which are incorporated into the software package OSPEX and used to fit the joint Fermi Gamma-ray Burst Monitor (GBM)/Large Area Telescope (LAT) spectrum of the 2010 June 12 solar flare, providing a statistically acceptable result.

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[*]Speaker

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1. Introduction

Solar flares are transient events that usually occur in the active regions of the solar atmosphere, leading to a sudden intense brightening observed over a small area on the Sun's surface. They involve an energy release of the order of 10^{27} to 10^{32} ergs typically in 10's of seconds to 10's of minutes, resulting in the emission of radiation covering virtually the entire range of the electromagnetic spectrum, from radio to γ-rays [1]. According to the standard model of solar flares [2], the energy stored in the magnetic field is released in the corona by the process called magnetic reconnection, heating the magneto-active plasma and accelerating electrons and ions to high energies. The heated magneto-active plasma produces emission of visible, infrared, and ultraviolet radiation, as well as soft X-rays by bremsstrahlung of thermal electrons. The accelerated (non-thermal) electrons trapped in the coronal magnetic loops produce radio and microwave radiation by synchrotron emission, as well as hard X-rays and γ-rays by bremsstrahlung as they precipitate into the chromosphere and photosphere. The accelerated ions precipitating from the corona into the chromosphere and photosphere produce γ-rays by interactions with the nuclei from the ambient solar atmosphere.

In recent works [3, 4] we have demonstrated the potential of the particle physics code FLUKA [5, 6] as an effective tool for the simulation of nuclear processes in the context of solar flares. FLUKA is a general purpose package of integrated routines for Monte Carlo simulation of particle transport and interactions in arbitrary materials. The code includes robust models for electromagnetic, hadronic and nuclear interactions, sufficiently detailed for it to be a useful tool for calculating all physical processes relevant to the γ-ray spectra observed in solar flares. Here, we illustrate the use of FLUKA to calculate γ-ray spectra expected from solar flare energetic ion distributions. From these model spectra we build templates which are incorporated into the software package OSPEX [7] and used to fit the joint Fermi Gamma-ray Burst Monitor (GBM)/Large Area Telescope (LAT) spectrum of the 2010 June 12 solar flare.

2. Solar Flare Model and γ-ray Spectrum Calculation

In our simulations we consider a model in which beams of primary accelerated ions are injected into a target with characteristics similar to those of the ambient solar atmosphere. We adopt a simple plane-parallel geometry and build a cubic box centered at the origin of a Cartesian coordinate system (*Ox*, *Oy*, *Oz*). The *z*-coordinate corresponds to the vertical depth in the ambient solar atmosphere. A *xy*-plane at $z = 0$ divides the cubic box into two half-spaces. The half-space at $z < 0$ represents the coronal region and, for simplicity, is just filled with vacuum (such that the particles are transported but no longer interact). The half-space at $z > 0$ represents the chromospheric/photospheric region and is filled with a dense, neutral material for which we assume a typical solar atmosphere composition with the abundances of ^{4}He, C, N, O, Ne, Mg, Al, Si, S, Ca and Fe nuclei relative to H given by [8]. The half-space at $z > 0$ is further divided into 52 layers with a vertical density profile given by the semi-empirical VAL-C model of the chromosphere [9] plus an additional layer corresponding to the photosphere with a density of 3.19×10^{-7} g/cm^3. The beams of primary accelerated ions are injected into the chromospheric/photospheric region from a point located at a distance z_0 above and very close to the *xy*-plane at $z = 0$. We assume an "impulsive-flare" composition for the primary accelerated ions with abundances given by [10] and an α/proton ratio of 0.1.

We run separate simulations for the nuclear reactions involving each primary accelerated ion species i and the ambient atmosphere nuclei. The primary accelerated ions are assumed to have a downward isotropic angular distribution and a power-law energy distribution given by:

$$\frac{dN_i(E)}{dE} = A\,E^{-\delta} H(E_{max} - E)\,H\,(E - E_{min})\,, \tag{1}$$

where E is the kinetic energy per nucleon of the primary accelerated ion in an energy range from E_{min} = 1 MeV/nucleon to E_{max} = 1 GeV/nucleon, δ is the spectral index, H is the Heavyside function and A is a normalization factor.

The total photon spectrum is obtained by summing up the contributions from each primary accelerated ion species i weighted by their relative abundances $a_{acc,i}$:

$$\frac{d\Phi(E_{ph})}{dE_{ph}} = \sum_i a_{acc,i} \frac{d\Phi_i(E_{ph})}{dE_{ph}}\,, \tag{2}$$

We can also evaluate the components due to the direct reactions (which involve interactions of primary accelerated protons and α-particles with all ambient nuclei) and due to the inverse reactions (which involve interactions of primary accelerated ions heavier than α-particles with ambient nuclei of H and ^{4}He):

$$\frac{d\Phi_{dir}(E_{ph})}{dE_{ph}} = \frac{d\Phi_p(E_{ph})}{dE_{ph}} + a_{acc,\alpha}\frac{d\Phi_\alpha(E_{ph})}{dE_{ph}}\,, \quad \frac{d\Phi_{inv}(E_{ph})}{dE_{ph}} = \sum_{i \neq p,\alpha} a_{acc,i}\frac{d\Phi_i(E_{ph})}{dE_{ph}}\,. \tag{3}$$

In Figure 1 we show the total γ-ray spectrum, along with the components due to the direct and inverse reactions, obtained by considering primary accelerated ions with a power-law energy distribution of spectral index δ = 4. As one can observe, the spectrum exhibits all the typical structures of γ-ray spectra observed in solar flares: positron annihilation line, neutron-capture line, nuclear de-excitation γ-ray lines and continuum emission components from neutral-pion decay and bremsstrahlung of secondary electrons and positrons from charged-pion decay.

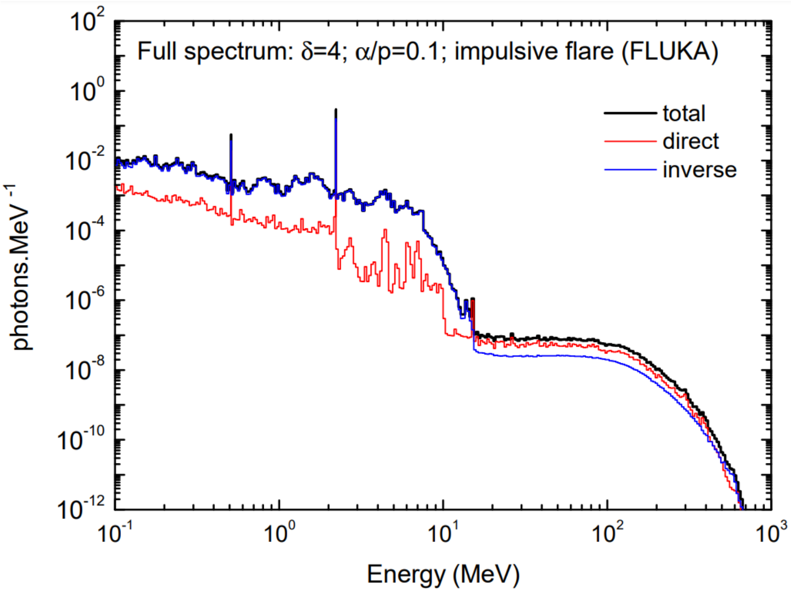

Figure 1 - γ-ray spectrum obtained with FLUKA by considering primary accelerated ions with a power-law energy distribution of spectral index δ = 4 [3].

3. Fit to the γ-ray Spectrum of the 2010 June 12 Solar Flare

The GOES M2-class solar flare of 2010 June 12 (SOL2010-06-12T00:57) was observed by the two instruments of the Fermi satellite [11], the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT), in the NOAA active region 11081 at the heliographic coordinates N23W43. Using OSPEX, we fit the GBM background-subtracted spectrum in the energy range from 300 keV to 10 MeV, accumulated between 00:55:40 and 00:58:50 UT, and the LAT background-subtracted spectrum in the energy range from 30 to 300 MeV, accumulated in the same time interval. In Figure 2 we show the result for the best fit to the joint GBM/LAT photon spectrum obtained using FLUKA templates for the direct and inverse components of the γ-ray spectrum, which are built from simulations considering primary accelerated ions with a power-law energy distribution of spectral index δ = 4. The fit is implemented by combining the FLUKA templates with a single power-law function (*1pow*) and a power-law function with an exponential cutoff (*1pow-exp*) to account for the bremsstrahlung of primary accelerated electrons, which are provided as standard fitting components by OSPEX. We assess separately the quality of the fit in the GBM and LAT energy ranges by evaluating the reduced chi-square χ_r^2. For the GBM spectrum in the energy range from 300 keV to 10 MeV the fit is very reasonable ($\chi_r^2 = 2.89$), while for the LAT spectrum in the energy range from 30 to 300 MeV the fit is only satisfactory ($\chi_r^2 = 6.19$).

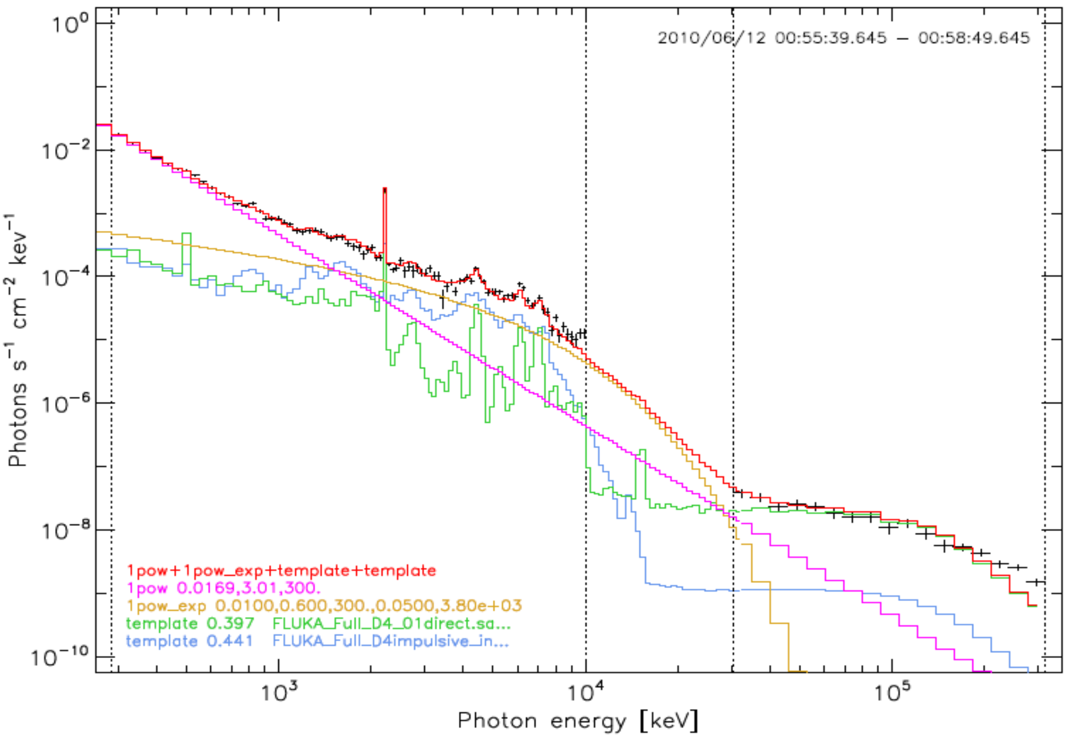

Figure 2 - Best fit to the joint GBM/LAT photon spectrum of the 2010 June 12 solar flare obtained using FLUKA templates for the direct and inverse components of the γ-ray spectrum [3].

A full analysis of these data would search for a best fit across several templates calculated using different values of ion energy spectral index δ. The exercise presented here, with a fixed value δ = 4, nonetheless shows that the FLUKA simulations can give a description consistent with GBM and LAT data, across the photon energy range from 300 keV to 300 MeV.

4. Summary and Final Remarks

In this work we illustrate the use of the Monte Carlo code FLUKA to calculate γ-ray spectra expected from solar flare energetic ion distributions. From these model spectra we build templates which are incorporated into the software package OSPEX and used to fit the joint Fermi GBM/LAT spectrum of the 2010 June 12 solar flare, providing a statistically acceptable result. To the best of our knowledge, the fit carried out with the FLUKA templates for the γ-ray spectrum can be regarded as the first attempt to use a single code to implement a self-consistent treatment of the several spectral components in the energy range from ~100's keV to ~100's MeV.

Acknowledgments

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