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Contribution of energetic ion secondary particles to solar flare radio spectra

Jordi Tuneu[1], **Sérgio Szpigel**[1], **Guillermo Giménez de Castro**[1] **and Alexander MacKinnon**[2]

[1]Center for Radio Astronomy and Astrophysics, Mackenzie Presbyterian University, Sao Paulo, Brazil
email: `jordituneu@protonmail.com`
[2]School of Physics and Astronomy, University of Glasgow, Glasgow, UK
email: `alexander.mackinnon@glasgow.ac.uk`

Abstract. Recent observations of solar flares at high frequencies have provided evidence of a new spectral component with flux increasing with frequency in the THz range. Its origin remains unclear. Here, we present preliminary results of simulations of synchrotron emission due to secondary positrons and electrons produced in nuclear reactions during a solar flare. We use the general purpose Monte-Carlo code FLUKA to obtain distributions of secondary particles resulting from accelerated protons interacting in the solar atmosphere. We calculate the synchrotron radiation spectrum and compare our results to observations of the November 4th, 2003 burst event.

Keywords. Solar flares, Secondary positrons and electrons, Synchrotron radiation

1. Introduction

Systematic observations of solar flares at high frequencies (0.2 and 0.4 THz) with the *Solar Submillimeter Telescope* (SST) at the *El Leoncito* observatory in Argentina have provided evidence of a new spectral component with flux increasing with frequency in the THz range (Kaufmann *et al.* 2002, Kaufmann *et al.* 2004). This new component occurs simultaneously but separated from the well-known microwave spectral component which reaches its maximum flux typically at 10's of GHz. Its nature remains unclear (see Krucker *et al.* (2013) for a review on observations and possible radiation mechanisms).

The γ-ray continuum tells us that $\sim GeV$ ions are present in some flares (Vilmer *et al.* 2011). These will produce secondary positrons and electrons with energies in the range from 0.1 to 1 GeV by a variety of mechanisms: pion decay, Compton scattering and pair production of γ-ray photons as well as "knock-on" electrons. These secondary positrons and electrons will radiate in the sub-THz range of frequencies via synchrotron emission. Silva *et al.* (2007) and Trottet *et al.* (2008) both found that the populations of secondaries implied by observed γ-ray fluxes were too low to account for the sub-THz observations. Trottet *et al.* (2008) did not discard this mechanism, however, noting that a more detailed treatment of secondary particle transport was needed.

2. Simulation Methods and Results

We use FLUKA (Ferrari *et al.* 2005), a general-purpose Monte-Carlo code for calculations of particle transport and interactions in matter, to simulate accelerated protons colliding with a thick target with Asplund *et al.* (2009) chemical abundances and producing secondary particles through nuclear reactions (see also MacKinnon *et al.* (2016)).

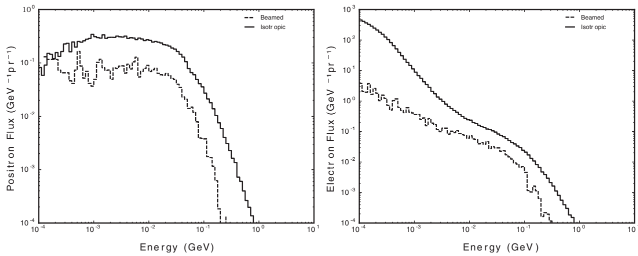

Figure 1. Energy distributions of secondary positrons and electrons.

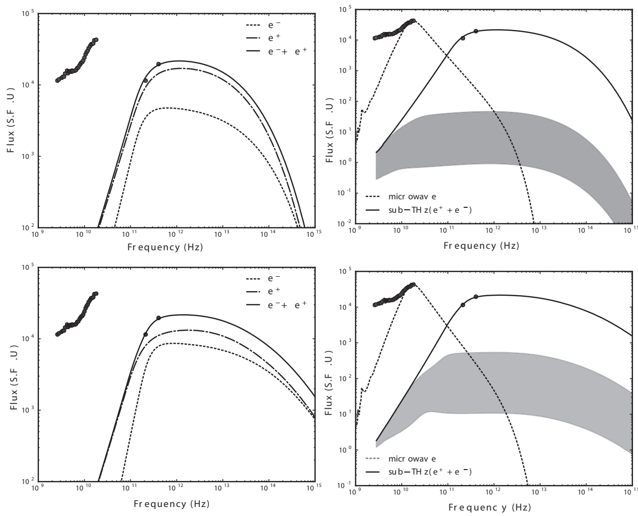

Figure 2. Synchrotron radiation spectra due to secondary positrons and electrons calculated for the downward unidirectional beam (top) and the downward isotropic beam (bottom).

We consider accelerated primary protons with a power-law energy distribution and two different angular distributions: downward unidirectional and downward isotropic. In each case, we monitor the energy distributions of secondary positrons and electrons as they cross from the dense atmosphere to the corona. We assume that these particles are trapped in a magnetic field and use a code based on Ramaty's algorithm (Ramaty *et al.* 1994) to calculate the resulting synchrotron radiation spectrum. We determine the total number of accelerated primary electrons by fitting the observed spectrum in the microwave range of frequencies, and estimate the associated number of primary protons via the correlation between primary electrons and protons found by Shih *et al.* (2009).

In Fig. 1 we show the energy distributions of secondary positrons and electrons calculated for primary protons with a power-law energy distribution in the range from 0.2 to 10 GeV and spectral index $\delta = 2$ in the case of a downward unidirectional beam and in the case of a downward isotropic beam. As one can observe, the energy distributions of secondary positrons and electrons strongly depend on the angular distribution of primary protons. Knock-on electrons are numerically dominant over pion decay electrons below a few MeV, with possible implications for emission at cm wavelengths, particularly so in the case of a downward isotropic beam. In Fig. 2 we show the synchrotron radiation spectra due to secondary positrons and electrons calculated for the downward unidirectional beam (top) and the downward isotropic beam (bottom). In the left panels, we show the results obtained by considering the number of protons as a free parameter, N_p^{free}, which

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is adjusted to fit the spectrum of the November 4th, 2003 flare at sub-THz frequencies. The values of the other model parameters used in the calculations are kept fixed: magnetic field strength $B = 1000\,G$, viewing angle $\theta = 45°$, source size $\phi_s = 0.3''$, and electronic plasma density $n_p = 1.0 \times 10^8\,cm^{-3}$. In the right panels, we show the results obtained by using the number of primary electrons adjusted to fit the observed spectrum at microwave frequencies to constrain the number of protons, finding a minimum and a maximum number of protons, N_p^{min} and N_p^{max}, based on the spread of the correlation by Shih *et al.* (2009). In Table 1 we compare the values for N_p^{free}, N_p^{min} and N_p^{max} and the corresponding number of secondary positrons and electrons found in each case.

Table 1. Number of protons, positrons and electrons found in the calculations of the synchrotron radiation spectra for the downward unidirectional beam and the downward isotropic beam.

PROTONS	N_p^{free}	N_p^{min}	N_p^{max}
Downward unidirectional	9.0×10^{33}	1.3×10^{30}	6.4×10^{31}
Downward isotropic	2.6×10^{33}	1.3×10^{30}	6.4×10^{31}
POSITRONS	$N_{e^+}^{free}$	$N_{e^+}^{min}$	$N_{e^+}^{max}$
Downward unidirectional	3.6×10^{31}	5.1×10^{27}	2.5×10^{29}
Downward isotropic	3.8×10^{31}	1.9×10^{28}	9.4×10^{29}
ELECTRONS	$N_{e^-}^{free}$	$N_{e^-}^{min}$	$N_{e^-}^{max}$
Downward unidirectional	3.1×10^{31}	4.4×10^{27}	2.2×10^{29}
Downward isotropic	2.4×10^{32}	1.2×10^{29}	6.0×10^{30}

3. Final Remarks

We have used the Monte-Carlo code FLUKA to simulate the nuclear reactions of $\sim GeV$ ions precipitating into the dense atmosphere during a solar flare and obtain the energy distributions of the resulting secondary positrons and electrons escaping from the dense atmosphere to the corona. Our results show that secondary knock-on electrons are not negligible compared to secondary positrons. For a downward unidirectional beam of primary protons we obtain a ratio $N_{e^-}/N_{e^+} \sim 0.9$ and for a downward isotropic beam we obtain $N_{e^-}/N_{e^+} \sim 6.3$. The results obtained in calculations of the synchrotron radiation spectrum due to secondary positrons and electrons show that in the most favorable case (downward isotropic beam) the number of primary protons required to fit the increasing spectrum of the November 4th, 2003 flare at sub-THz frequencies is ~ 40 times more than the maximum number estimated from the correlation by Shih *et al.* (2009).

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