Contribution from Drell-Yan Processes to the Emission Spectrum in Solar Flares

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The recent discovery of a new and intense solar flare radiation spectral component with a maximum in the terahertz range has raised a great deal of interest. The origin of this component is still unknown, constituting a problem that goes beyond the application of canonical models used to describe the well-known microwave spectrum. In this work, we present preliminary results on the investigation of a possible contribution from electron-positron pairs produced in a Drell-Yan process to the emission of the terahertz component observed in solar flares.

Keywords: Drell-Yan processes; Solar emission spectrum; Terahertz component

I. INTRODUCTION

Solar flares are sudden and rapid releases of enormous amounts of energy in the solar atmosphere, involving acceleration of particles, plasma heating and bulk mass motions. It is a general believe that they occur when the energy stored in magnetic loops that have built up in the active regions around sunspots is suddenly released, in a process called magnetic reconnection [1]. During the restructuring of the magnetic fields in such a process both electrons and ions are accelerated to high energies and radiation is emitted covering virtually the entire electromagnetic spectrum, from radio-waves to gamma-rays [2].

The recent discovery of a new and intense solar flare radiation component with a maximum in the shorter submillimeter to far infrared range has raised a great deal of interest, confirming theoretical suggestions and experimental evidences proposed for more than twenty years. This new component, which in the frequency domain has a peak in the terahertz range (0.1-100 THz), was identified by Kaufmann et al. [3] during the observation of the 2003 November 4 large solar flare.

The origin of the terahertz component observed during this solar flare is still unknown, constituting a problem that goes beyond the application of canonical models used to describe the well-known microwave spectrum observed at frequencies below 100 GHz. In such canonical models, the processes of energy generation during the flare impulsive phase are generally attributed to a population of relativistic electrons producing microwaves by synchrotron emission and X-rays by collisions in denser regions of the solar atmosphere [4].

Nevertheless, a few early models were proposed to explain solar flare radio emission at frequencies higher than 100 GHz considering electrons with energies much larger than the energies assumed to explain the usual microwaves (> 10 MeV), such as free-free thermal bremsstrahlung [5] and synchrotron emission by ultra-relativistic electrons [6].

In this work we investigate the contribution from Drell-Yan processes to the emission spectrum in solar flares. We present preliminary results on the calculation of the energy spectrum for electron-positron pairs produced in a Drell-Yan process from proton-proton collisions in the solar atmosphere and discuss its possible contribution to the terahertz component observed in solar flares.

II. THE OBSERVATION OF THE NEW TERAHERTZ SOLAR FLARE COMPONENT

The new terahertz component was detected during the observation of the 2003 November 4 solar flare using the Solar Submillimeter Telescope (SST) at the Leoncito Observatory in Argentina, built to extend the range of solar flare observations to frequencies above 100 GHz [7]. The SST detected this new component with flux increasing between 212 and 405 GHz, along with the well-known microwave component, but distinguished from it. In Fig. 1 (Kaufmann et al. [3]), we show the time profiles of emissions at 212 and 405 GHz, in solar flux units.

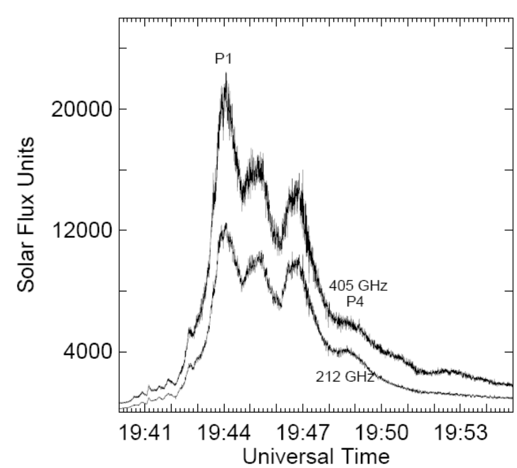

FIG. 1: Time profiles of the 2003 November 4 solar flare emissions at 212 GHz and 405 GHz (Kaufmann et al. [3]).

In Fig. 2 (Kaufmann et al. [3]) we show the spectra for the major peak P1 and the smaller peak P4, along with the corresponding well-known gyrosynchrotron microwave com-

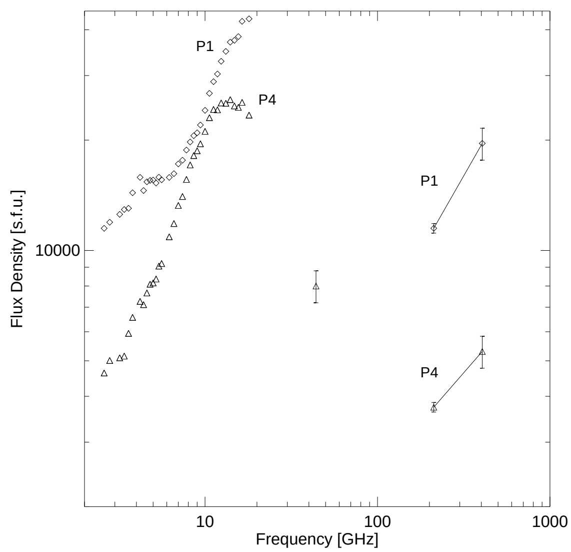

FIG. 2: Spectra for peaks P1 and P4 along with the corresponding microwave components (Kaufmann et al. [3]).

ponents at 15.6 GHz for comparison. As can be seen from the figure, the flux density is much larger at 405 than at 212 GHz for both peaks, indicating a maximum spectral emission lying within the terahertz range.

Recently, Kaufmann and Raulin [8] proposed a mechanism to explain the new terahertz component in which beams of ultra-relativistic electrons produce incoherent synchrotron radiation (ISR) with maximum in the terahertz range, further undergoing density modulations that may generate microbunching instabilities producing the intense broadband coherent synchrotron (CSR) observed at microwaves. This process is similar to what happens in laboratory accelerators with high energy electrons beams in storage rings [9].

In another recent work, Sakai et al. [10] proposed an interpretation for the terahertz component in terms of a plasma emission mechanism in which Langmuir waves, generated when relativistic electron beams propagate into the high density region corresponding to the solar photosphere, are converted in electromagnetic waves.

III. SYNCHROTRON EMISSION FROM POSITRONS IN SOLAR FLARES

A possibility that has also been considered to explain the terahertz component is the synchrotron emission by high-energy positrons [11], whose presence during solar flares is confirmed by the observation of the 511 keV gamma-ray positron-electron annihilation line [12].

The main mechanism for positron production in solar flares is the decay of pions produced by nuclear interactions of flare-accelerated protons with protons or alpha-particles in the ambient solar atmosphere [13], such as in the following mode:

$$\begin{aligned} &\mathrm{p}+\mathrm{p}(\alpha) \to \pi^+ + \mathrm{X} \\ &\pi^+ \to \mu^+ + \nu \ , \ \ \mu^+ \to \mathrm{e}^+ + 2\nu . \end{aligned} \tag{1}$$

Another contribution is due to the decay of radioactive positron-emitter isotopes such as ^{10}C, ^{11}C, ^{12}N, ^{13}N and ^{15}O which are produced in nuclear interactions of flare-accelerated protons and alpha-particles with ambient heavy nuclei [14]. The importance of these processes for positron production depends on the cross sections and the assumed elemental and isotopic abundances.

In a comparative study of different emission mechanisms that could explain the terahertz component, Valio et al. [11] estimated the synchrotron emission from 1 to 1000 MeV positrons. A fitting for the observed terahertz spectrum shown in Fig. 2 was calculated using a simplified version of an energy spectrum for positrons produced from pion decay evaluated by Murphy et al. [13].

Although a good fit was obtained for the 212 GHz and 405 GHz data points, a total number of positrons had to be assumed which was approximately 200 times larger than the 10^{30} positrons inferred from measurements of the 511 keV annihilation line. This result gives the main motivation of this work. Electron-positron pairs, produced in a Drell-Yan process at high energies, can carry large momenta and, in principle, could provide an extra contribution to the mechanism of synchrotron emission by positrons in the terahertz range.

IV. SPECTRUM OF POSITRONS PRODUCED IN A DRELL-YAN PROCESS

The Drell-Yan process is a high-energy reaction in which a dilepton pair l^+l^- is produced from quark-antiquark annihilation in a nucleon-nucleon (nucleus-nucleus) collision [15]. The differential cross-section for dilepton pair production in a Drell-Yan process is a standard calculation in perturbative QCD. In terms of the dilepton pair invariant mass M and the Feynman scaling variable x_F for the l^+l^- pair, if one considers only the lowest order diagram (*i.e.* quark-antiquark annihilation going to a virtual photon which subsequently decays into an l^+l^- pair), the cross-section for the process at Leading Order (LO) can be written as:

$$\begin{aligned} \frac{d^2\sigma}{dM^2 dx_F} \;&=\; \kappa \frac{\hat{\sigma}(M)}{sN_c} \sum_f^{N_f} \left(\frac{e_f}{e}\right)^2 (x_F^2 + 4M^2/s)^{-1/2} \times \\ &\times \; \left[q_f^A(x_1)\bar{q}_f^B(x_2) + \bar{q}_f^A(x_1) q_f^B(x_2) \right] , \end{aligned} \tag{2}$$

where $N_c(=3)$ is the number of colors, e_f is the charge of quark with flavor f $(=u,d)$, s is the square of the total energy in the nucleon-nucleon collision center-of-mass frame, $\hat{\sigma}(M)$ is the elementary cross-section for the $q\bar{q}$ annihilation process and $q_f^A(x_1)$ $(\bar{q}_f^A(x_1))$, $q_f^B(x_2)$ $(\bar{q}_f^B(x_2))$ are the quark (antiquark) distribution functions for the nucleons A and B.

The factor κ accounts for the higher-order QCD corrections that enter the process and its value is typically 1-2. In what follows we shall assume $\kappa = 1$ and use the (LO) proton parton distribution functions, at a fixed scale $Q^2 = 1\,\mathrm{GeV}^2$, taken from [16] (GRV98 LO).

The quantities x_1 and x_2 are the nucleon momentum fractions carried respectively by partons in the projectile and target. They are related to M^2 and x_F by:

$$M^2 = s\,x_1 x_2 \;\; ; \;\; x_F = x_1 - x_2. \tag{3}$$

We consider the production of a positron-electron pair e^+e^- from a proton-proton collision and integrate over the total longitudinal momentum of the positron-electron pair in the center-of-mass frame $P_z = x_F\,\sqrt{s}/2$ for a fixed s to obtain the e^+/e^- energy distribution, given by:

$$\frac{dn^{e^\pm}}{dP_0^{e^\pm}}(P_0^{e^\pm}, s) = \frac{2}{\sigma_{\rm pp}^{\rm inel}(s)}\frac{d\sigma}{dP_0}, \tag{4}$$

where $\sigma_{\rm pp}^{\rm inel}(s)$ is the total cross-section for inelastic proton-proton collision which we shall take from Ref. [17], $P_0^{e^\pm}$ is the e^+/e^- energy in the proton-proton collision center-of-mass frame, P_0 is the total energy of the positron-electron pair and

$$\begin{aligned}\frac{d\sigma}{dP_0} &= \kappa\frac{4P_0}{s^{3/2}N_c}\int_0^{\sqrt{s}/2} dP_z\,\hat{\sigma}(M)\sum_f^{N_f}\left(\frac{e_f}{e}\right)^2 \times \\ &\times \frac{\left[q_f^A(x_1)\bar{q}_f^B(x_2) + \bar{q}_f^A(x_1)q_f^B(x_2)\right]}{(x_F^2 + 4M^2/s)^{1/2}}.\end{aligned} \tag{5}$$

In the calculation of the energy distribution we make the assumption $P_0 = 2P_0^{e^\pm}$ and take an average value for the total transverse momentum of the positron-electron pair P_T such that

$$M^2 = P_0^2 - P_T^2 - P_z^2 \approx P_0^2 - <P_T>^2 - P_z^2 \tag{6}$$

with $<P_T> \approx 0.3 - 0.5$ GeV.

We calculate the spectrum of e^+/e^- produced in the Drell-Yan process by considering collisions between flare-accelerated protons (projectile) and protons from the ambient solar atmosphere (fixed target) in the laboratory frame:

$$\frac{dN^{e^\pm}}{dE^{e^\pm}} = \int_{E_{\min}}^{E_{\max}} dE_p\,F(E_p)\,\frac{dn^{e^\pm}}{dE^{e^\pm}}(E^{e^\pm}, E_p), \tag{7}$$

where $E^{e^\pm}$ and E_p are respectively the kinetic energies of the e^+/e^- and the accelerated proton in the laboratory frame, given by

$$E^{e^\pm} = (\sqrt{s}P_0^{e^\pm} - 2m_{e^\pm}m_p)/2m_p \tag{8}$$

$$E_p = (s - 4m_p^2)/2m_p \tag{9}$$

Following Ref. [18] we use a power-law energy distribution function for the accelerated protons given by

$$F(E_p) = A\,E_p^{-\alpha}, \tag{10}$$

where A is a normalization constant picked so that the protons with energies in the range $E_{\min} \leq E_p \leq E_{\max}$ equals 1 and α is chosen in the interval $2 - 3$.

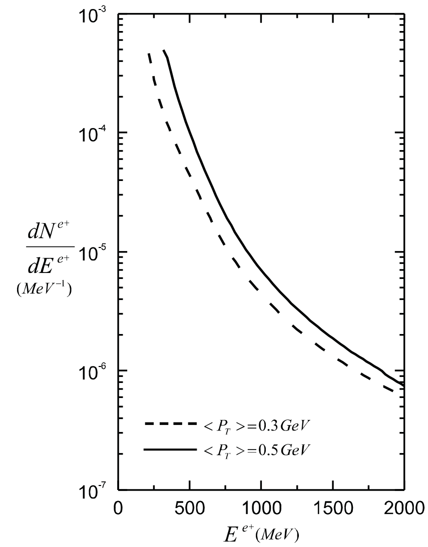

FIG. 3: Energy spectra of e^+ produced from Drell-Yan process for $<P_T> = 0.5$ GeV (solid) and $<P_T> = 0.3$ GeV (dashed).

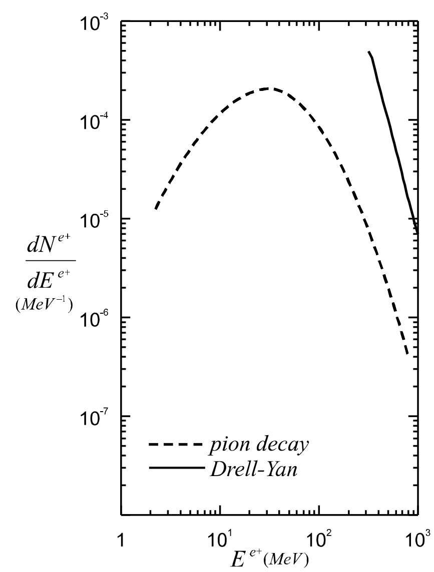

FIG. 4: Energy spectra of e^+ produced from the pion decay process obtained by Murphy et al. [13] (dashed line) and from the Drell-Yan process (solid line).

V. PRELIMINARY RESULTS AND DISCUSSION

In Fig. 3 we show the energy spectra for positrons produced in a Drell-Yan process obtained using Eq. 7 for two different average values for the total transverse momentum of the positron-electron pair: $<P_T> = 0.5$ GeV (solid line) and $<P_T> = 0.3$ GeV (dashed line). In both cases we have chosen $\alpha = 2$, $E_{min} = 1$ GeV and $E_{max} = 100$ GeV. As can be noted, the energy spectra have a maximum at the threshold positron kinetic energy (E^{e^+}) and decrease as the energy grows. Such threshold is determined by the condition that the square of the dilepton pair invariant mass M^2 in Eq. 6 must be greater than $4m_e^2$. Thus, for smaller values of $< P_T >$ the energy spectrum starts at lower values of E^{e^+}.

In Fig. 4 we show a comparison between our result for the positron energy spectrum obtained with $< P_T > = 0.5$ GeV (solid line) and the spectrum evaluated by Murphy et al. [13] for positrons produced from pion decay. As can be seen from the figure, for energies above ≈ 0.5 GeV a significant number of positrons can be produced from the Drell-Yan process in comparison to the number of positrons produced from the pion decay process, indicating a possible extra contribution to the synchrotron emission mechanism.

Although preliminary, these results are promising. We are currently refining the numerical calculations and testing for the sensitivity of the results on the parameters α, $< P_T >$, E_{min} and E_{max}. Our next step will be the evaluation of the synchrotron emission flux density in solar flares using a positron energy spectrum which takes into account the positrons produced both from the Drell-Yan process and the pion decay process.

By including the Drell-Yan contribution, we believe that the total number of positrons needed to fit the terahertz spectrum shown in Fig. 2 will be smaller than the number used by Valio et al. [11], yielding a result more compatible with the expected number of positrons inferred from the 511 keV annihilation line measurements.

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