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Gamma-ray emission from SEP interactions with solar wind ions

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Abstract: The detailed physics of solar energetic particles (SEPs) in solar flares is studied through remote imaging in the radio, hard X-ray and γ-ray energy ranges. However, the heliospheric SEP populations are observed only in situ by satellite measurements, which drastically limits our understanding of their spatial and temporal variations. Can those SEP populations be remotely imaged as are the solar SEPs? We consider the faint γ-ray emission from SEP interactions with solar wind (SW) ions as a possibility for large SEP events. Although the calculated intensities of the 4.44 and 6.13 MeV lines of ^{12}C and ^{16}O produced by the interactions of the SEPs with SW ions is essentially undetectable, the calculated intensity of π^0-decay γ-rays from a big GLE is above the observed Galactic and the expected near-solar γ-ray backgrounds and could be detected by a large-area space instrument.

Introduction

The production of energetic particles in solar flares has long been studied by their remotely observed radiative signatures. Nonthermal electrons with energies of tens of kilovolts and higher are detected in the microwave range by their gyrosynchrotron, plasma and transition radiation as they interact with coronal magnetic fields, plasmas and turbulence, respectively [1, 2]. Flare hard ($E >$ 20 keV) X-rays from electron bremsstrahlung have been observed by instruments on a number of spacecraft [3]. Through their various forms of γ-ray emission and neutron production high-energy ($E > 1$ MeV/nuc) flare ions have been detected by instruments on the *SMM*, *CGRO*, *Granat*, *Yohkoh*, and *RHESSI* spacecraft [3, 4, 5].

Solar energetic particles (SEPs) also depart the Sun in transient events and propagate through interplanetary space to 1 AU and beyond. In contrast to the remote observations of SEP populations in the dense regions and strong magnetic fields of solar flares, the low ambient particle densities and weak magnetic fields of interplanetary space have precluded remote observations of interplanetary SEPs in associated events. The spectral, temporal and spatial characterizations of the latter SEPs, detected only in situ by spacecraft far from the solar source regions and after significant scattering of the SEPs by turbulent magnetic fields, can not match those of the solar SEPs. Solar remote observations are used to predict the interplanetary SEP events with harmful consequences for human exploration of space [6], but the spatial, temporal, and spectral variations of the SEP events produced by the traveling shocks are poorly known.

Our understanding of interplanetary SEP events would benefit greatly from remote imaging of any signal produced by those SEPs, especially one produced in the near-Sun (< 0.1 AU) environment. The primary targets for radiative interactions of interplanetary SEPs are abundant elements in the solar wind (SW) and circumsolar dust grains. Galactic γ-ray line emission in the $E < 10$ MeV range is produced from cosmic-ray (CR) interactions with interstellar gas and dust grains (e.g., [7], [8], [9]). In the $E \geq 70$ MeV range π^0-decay is the dominant mechanism [10]. Here we consider whether γ-rays produced by the interaction of SEPs with the inner heliospheric ($r < 0.1$ AU) SW can be a tool for remote observation of SEP spatial distributions in large events. The concept is illustrated in Figure 1, which shows γ-rays imaged from the flare and interplanetary SEP populations.

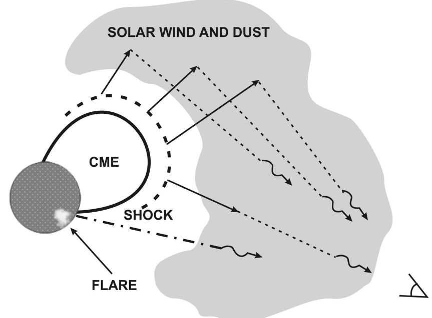

Figure 1: The γ-ray imaging of both flare and interplanetary SEP populations. The observer at 1 AU images solar-flare SEPs through their γ-ray emission (*dash-dotted line*) from the flare region. We propose that SEPs from a shock (*thick dashed line*) will propagate through SW and dust (*gray shading*) to produce weak γ-ray emission by SEP-SW interactions (*thin dashed lines*).

SEP-SW γ-ray line emission

For an intense low ($E < 30\,$MeV) energy SEP event we select that of 28 October 2003 [11]. From the *GOES-11* peak proton intensities $\sim 3{-}30$ MeV at 1 AU and 1800 UT on 28 October, we determine the differential proton spectrum
$dN/dE = 10^3 \times E^{-0.68}$ p cm^{-2}s^{-1}sr^{-1}MeV^{-1}. This energy spectrum is somewhat flatter than the event fluence spectrum shown in [12]. We also take a matching spectral shape for the alpha spectrum with the intensity reduced by a factor of 27.5, according to the abundances in Table 1 of [13] and consistent with the event fluence spectra of [12]. To calculate the γ-ray emission near the Sun at 0.05 AU ($10.75\,R_\odot$) we take an r^{-3} radial dependence for the SEP intensities [14], which enhances the 1 AU event peak spectrum by a factor of 8×10^3.

We take an r^{-2} dependence for the SW density, a nominal SW density at 1 AU of 5 protons cm^{-3}, and C and O relative abundances of 465 and 1000 compared with the proton abundance of 1.57×10^6 [13]. With these SW densities and SEP intensities we use the cross sections of [15] for production of the ^{12}C 4.44 MeV and ^{16}O 6.13 MeV lines to calculate the γ-ray line emission over an assumed source region of size $L = 0.05$ AU. For SEP proton interactions with ^{12}C and ^{16}O the calculated 4.44 and 6.13 MeV γ-ray intensities observed at 1 AU are $I = 2.3 \times 10^{-6}$ and 1.8×10^{-6} cm^{-2}s^{-1}sr^{-1}, respectively. The corresponding SEP α interactions with ^{12}C and ^{16}O yield intensities $\sim 20\times$ lower.

The ^{16}O content of the circumsolar dust is another possible source for the $6.13\,$MeV line. From the dust mass distribution at 0.1 AU from Figure 7 of [16], we get a range for the total mass density of $3 \times (10^{-25} - 10^{-24})$ g cm^{-3}. Even if O is half the dust mass, then the O density at 0.1 AU is $6 \times (10^{-3} - 10^{-2})$ cm^{-3}, one to two orders of magnitude lower than the SW O abundance and therefore not a significant additional source of O ions for the $6.13\,$MeV γ-ray line. The O abundances, however, could be locally substantially enhanced by the passage of Kreutz Sun-grazing comets.

The γ-ray line emission generated by SEP interactions with the SW will be observed against background continuum emission from two sources. The diffuse Galactic background has been modeled in [17] with measurements from *CGRO*. Figure 2 shows the intensity spectrum of the inner Galaxy, where the galactic background is highest. At 6.13 MeV that intensity is $\sim 2 \times 10^{-4}$ MeV^{-1}cm^{-2}s^{-1}sr^{-1}. Away from the Galactic center the primary background is the diffuse extragalactic component of perhaps $\sim 2 \times 10^{-5}$ MeV^{-1}cm^{-2}s^{-1}sr^{-1}, which still exceeds the SEP γ-ray line emission by an order of magnitude, assuming an energy resolution of $\sim 1\,$MeV.

A second background emission source, produced by inverse Compton (IC) scattering of solar optical photons by Galactic CR electrons [18] and [19], is a diffuse continuum source with a broad angular distribution peaked in the solar direction as viewed from the Earth. Figure 3 shows calculated differential IC intensities [18] for different solar elongation angles and assumed electron modulation potentials. At a 1° elongation angle ($\sim 4R_\odot$) the differential intensity of IC emission at 6.13 MeV is $\sim 10^{-5}$ MeV^{-1}cm^{-2}s^{-1}sr^{-1}, also about an order of magnitude greater than our calculated 6.13 MeV line emission I of $\sim 2 \times 10^{-4}$ cm^{-2}s^{-1}sr^{-1}, so the detection of that line from even an extremely large SEP event appears hopeless. To confirm this, we calculate that the 28 October event would produce $\ll 1$ count/hour in the $GLAST$ Burst Monitor.

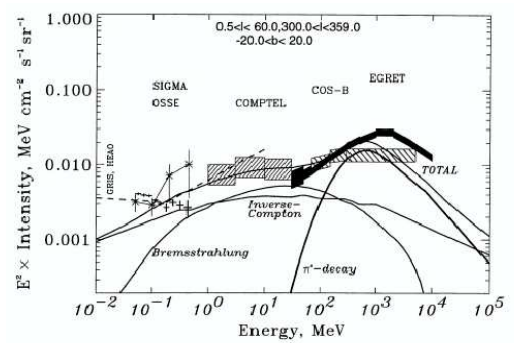

Figure 2: γ-ray intensity spectrum of the inner Galaxy (from [20]). Observations from *CGRO* are shown with modeled emission contributions.

SEP-SW γ-ray π^o-decay emission

Collisions of $E > 300$ MeV SEPs with SW ions produce π particles, which decay to produce γ-ray continuum [21, 3]. The $E > 50$ MeV bremsstrahlung and annihilation radiation from charged π particles is small compared with the 2-γ decay of the π^0 [21]. For a calculation of the maximum expected π^0-decay emission from SEP interactions with the SW ions, we use the estimated peak proton spectrum of the large GLE event of 20 January 2005. With the integral $E > 100$ MeV proton intensity of [12] and an assumed E^{-2} differential power law we derive a spectrum of $dN/dE = 10^5 \times E^{-2}$ p cm^{-2}s^{-1}sr^{-1}MeV^{-1} at 1 AU. We again assume r^{-3} and r^{-2} radial dependences for the SEP and SW intensities respectively. To calculate the π^0 production of the 20 January SEPs at $r = 0.05$ AU and an assumed line of sight depth of 0.05 AU, we integrate the SEP spectrum with the π^0 production cross section given in equation (1) of [22]. The p-α interactions yield a result more than $10\times$ smaller than that for the p-p interaction. We assume that all π^0 particles decay into pairs of γ-ray photons of energy $E \sim 70$ MeV each. The calculated intensity of π^0-decay γ-rays at 1 AU is ~ 0.3 (cm^{2}s sr)$^{-1}$. Assuming a broad distribution over the range $40 < E < 150$ MeV gives a differential distribution I of $\sim 3 \times 10^{-3}$ MeV^{-1}cm^{-2}s^{-1}sr^{-1}.

We now compare the calculated peak π^0-decay γ-ray intensity with the observed Galactic and calculated solar IC background sources (Figures 2 and 3) to determine whether observation of those γ-rays is feasible. The Galactic background (Figure 2) is about 2×10^{-6} (cm^2 s sr MeV)$^{-1}$, and the solar IC background at 1^o elongation (Figure 3) is another factor $\sim 10 \times$ smaller. The calculated π^0-decay γ-ray emission from the 20 January SEP event is therefore three orders of magnitude above the Galactic background. Away from the Galactic center, which the Sun crosses in December, we can expect another order of magnitude decrease in the intensity, when the diffuse extragalactic background dominates (see Figure 3). The large 60^o inclination between the ecliptic and galactic planes should favor the relatively low extragalactic background of perhaps $\sim 2 \times 10^{-7}$ MeV^{-1}cm^{-2}s^{-1}sr^{-1} most of the year.

Another π-decay background source in the $E > 50$ MeV range is due to collisions of Galactic cosmic rays (GCRs) with the solar atmosphere. The $E > 100$ MeV flux from the solar disk was calculated to be $\sim 10^{-7}$ cm^{-2}s^{-1} [23], a counting rate of $\sim 2 - 8$ photons/day for the *GRO* EGRET instrument with an effective area of the order of 1000 cm^{-2}. Combining a set of six solar observations with EGRET, [24] established an upper limit of 2.0×10^{-7} photons cm^{-2}s^{-1} for the solar $E > 100$ MeV flux.

Although the calculated intensity is well above the background levels, detection of the SEP π^0-decay γ-rays is feasible only with an adequately large detector. For this purpose we again consider the appropriate detector on the *GLAST* mission, in this case the Large Area Telescope (LAT), which has an effective area A of ~ 2000 cm^2 (http://www-glast.slac.stanford.edu /software/IS/glast_lat_performance.htm). Making the assumption of a 1-hr event duration T and an $\Omega = 0.003$ sr, the number of detected LAT γ-ray counts over the $\sim 50 - 150$ MeV range is $I \times A \times \Omega \times T = 0.3 \times 2000 \times 0.003 \times 3600 = 6 \times 10^3$ counts. This is well above the ~ 1 count/hr upper limit for the π-decay γ rays from GCR-Sun interactions.

A detector with the area of the LAT and a good angular resolution should be able to observe the transient SEP π^0-decay signal over the solar IC and extragalactic diffuse backgrounds. With low angular resolution, however, the detector background counting rates may present a challenge for a positive detection of our calculated γ-ray emission.

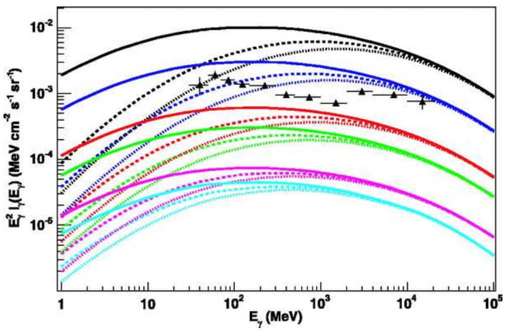

Figure 3: Differential intensities of IC emission from scattering of solar photons by cosmic-ray electrons for selected solar elongation angles ranging from 0.3^o (*top line sets*) to 180^o (*bottom line sets*) from [18]. *Solid, dashed, and dotted lines* are different assumed CR electron modulation potentials. *Data points* are diffuse extragalactic γ-ray intensities.

Conclusions

We have selected two very energetic SEP events to calculate the γ-ray line and π^0-decay intensities from collisions with SW ions. The intensities were compared with the backgrounds from the Galactic/extragalactic and solar emissions. The ^{16}O 6.13 MeV and ^{12}C 4.44 lines are far too weak for detection. However, with sensitive detectors such as the LAT of the approaching *GLAST* mission detections of $\sim$ 70 MeV π^0-decay emission should be possible for GLEs with $E > 100$ MeV intensities within an order of magnitude of the 20 January event [12]. The assumed rapid radial decrease from the Sun of both the SEP intensities and SW density suggest that any SEP event γ-ray emission regions will be closely confined to the solar vicinity. Simultaneous γ-ray emission from associated solar flares could be much larger than the emission from the interplanetary SEPs. Unless the flare occurs behind the limb or well before the SEP-SW interactions, a solar occulter or good angular resolution would be required to separate the interplanetary γ rays from the flare emission.

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