# Interaction of GeV protons with circumsolar dust grains

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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 $\gamma$-ray energy ranges. However, the heliospheric SEP populations are observed only in situ by satellite measurements, which drastically limits our understanding of their properties, such as their spatial and temporal variations. Can those SEP populations be remotely imaged as are the solar SEPs? We consider the faint $\gamma$-ray emission from SEP interactions with circumsolar dust grains as a possibility. The $\gamma$-ray line flux produced by the interactions of the SEPs with dust grains in large SEP events is calculated. We select the 6.1 MeV line of $^{16}$O as the best candidate for detection. The calculated intensities are compared with the observed Galactic $\gamma$-ray background and expected near-solar emission from inverse-Compton scattering of solar photons by cosmic-ray electrons.

## 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 gyrosynchroton, plasma and transition radiation as they interact with coronal magnetic fields, plasmas and turbulence, respectively [1, 24]. Flare hard (E $>$ 20 keV) X-rays from electron bremsstrahlung have been observed by instruments on a number of spacecraft [10]. Through their various forms of $\gamma$-ray emission and neutron production high-energy (E $>$ 1 MeV/nuc) flare ions have been detected by instruments on the $Solar Maximum Mission$, $Compton Gamma-Ray Observatory$ ($CGRO$), $Granat$, and $Yohkoh$ spacecraft [10, 26]. Observations of flare X-rays and $\gamma$ rays by the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) currently provide the most definitive spectral, spatial, and temporal information on solar flare electrons and ions (e.g., [19]).

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 preclude remote observations of interplanetary SEPs in associated events. The latter SEPs are detected only in situ by spacecraft detectors at a single or several locations far from the solar source regions and only after significant scattering of the SEPs by turbulent magnetic fields. It is therefore impossible to match the inferred spectral, temporal and spatial characterizations of the solar particle populations with similar characterizations of the interplanetary populations.

The longstanding question of how the interplanetary SEP populations are related to those of the solar flares [28, 18] has been addressed by comparing solar flare $\gamma$-ray line fluences with peak in situ intensities of associated interplanetary SEP ion events [5]. That comparison depends on the assumption that the interplanetary SEP peak intensities observed in situ scale with the total interplanetary populations. Comparisons of the total energies of interplanetary SEP events with those of their associated flares and CMEs also require important assumptions about angular extents of SEP shock sources, numbers of SEP crossing times at

1 AU, and longitudinal and latitudinal gradients of the SEP intensities [8].

Solar remote observations are used to predict the interplanetary SEP events with harmful consequences for human exploration of space [32]. However, some SEP events appear to originate from regions far behind the solar limb [6] with no solar flare signatures. Current efforts are based on relating properties of SEP events to those of observed coronal mass ejections, the link between the two phenomena being the assumed acceleration of SEPs by CME-driven fast MHD shocks [9, 14]. However, the spatial, temporal, and spectral variations of the SEP events produced by the traveling shocks are poorly known. Rough averages of radial and azimuthal gradients of SEP intensities and fluences have been derived from the in situ observations of several spacecraft [17], but a large scatter of SEP event peak intensities and timescales remains unexplained [13].

It is clear that 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. Energetic neutral atoms (ENAs) produced by charge exchange between energetic ion populations in corotating interaction regions (CIRs) and neutral H and He atoms from interstellar space are one possibility. In [**?**], CIRs could not be ruled out as a possible source of observed 25-100 keV ENAs and also suggested that ions from CME-driven shocks could be another source of ENAs. The LENA instrument on $IMAGE$ has observed enhanced ENAs in association with a CME-driven shock near the Earth, presumably from energetic shock ions interacting with neutrals in the magnetosheath [7]. However, interstellar neutrals are depleted near the Sun and charge exchange works only at E $>$1 MeV, so ENAs are not feasible for remote sensing of SEPs.

The negligible radiative interactions of SEPs with both magnetic fields and solar wind plasmas near the Sun leaves only circumsolar dust grains as a SEP radiative target. $\gamma$-ray line emission is produced from cosmic-ray (CR) interactions with interstellar gas and dust grains (e.g., [20, 27, 31]), and the most promising lines are at 0.847, 1.369, 1.779, and 6.129 MeV from $^{56}$Fe, $^{24}$Mg, $^{28}$Si, and $^{16}$O, respectively. The line profiles are very narrow ($<$ 5 keV) when the stopping times of the recoil nuclei are short compared to the lifetimes of their excited states [20], which may occur in sufficiently thick ($\geq 0.3$ $\mu$m) dust grains [31]. Here we consider whether $\gamma$-rays produced by the interaction of SEPs with circumsolar dust can be a tool for remote observation of SEP spatial distributions in large events.

## Emissivity of $^{16}$O 6.13 MeV $\gamma$-ray line

For the optimum expected $\gamma$-ray emission from the SEP-dust interactions, we estimate the proton spectrum of a large gradual SEP event, assume a circumsolar dust composition and density distribution for the SEP-dust interaction, and select preferred line(s) for an emissivity calculation. The calculated $\gamma$-ray intensities must then be compared with background sources to determine whether observation of the expected intensities is feasible.

From the recent solar cycle we select the two large SEP events of 28 October 2003 and 20 January 2005 [22]. We approximate the peak proton spectra above 10 MeV at 1 AU for 1600 UT on 28 October from the $GOES-10$ proton detector by dI/dE = $3\times10^6$ E$^{-3}$p/cm$^2$s sr MeV and for 0900 UT on 20 January from the $GOES-11$ detector with dI/dE = $7\times10^4$ E$^{-2}$ p/cm$^2$ s sr MeV. To determine the energy spectrum at 15 Rs we assume an r$^{-3}$ radial dependence, somewhat steeper than recent measurements [17], which increases the above event peak spectra by a factor of $3.15\times10^3$. We assume that the SEPs are forward beamed after acceleration over the range 5 to 15 Rs by a shock moving $\sim$ 10 Rs/hr to produce the peak SEP intensities.

To calculate the dust mass we assumed the dust mass distribution at 0.1 AU from Figure 7 of [11]. The differential grain density at $\sim10^{-12}$ g is $\sim10^{-13}$-$10^{-12}$cm$^{-3}$. Integrating over the mass range $10^{-12}$ to $10^{-7}$ g, approximated by a –4/3 power law, we get a range for the total mass density of $3\times$ ($10^{-25}$–$10^{-24}$) g cm$^{-3}$. The grain composition of sungrazing comets, which supply dust to the 0.1 AU region, is assumed rich in olivine and pyroxene (e.g., [2, 4]), of which O is a dominant constituent. We assume that half the mass of the dust consists of O and that the most intense $\gamma$-ray line resulting from proton collisions from dust will be the $^{16}$O 6.13 MeV line.

All protons of E $>$ 100 keV will completely traverse dust grains of diameters $\geq$ 1 $\mu$m and the grains are also transparent to the 6.13 MeV $\gamma$-rays, so we assume an optically thin medium for both the SEPs and $\gamma$-rays. The column density of $^{16}$O traversed by the protons over an assumed radial distance of $\sim$ 15 Rs is $\sim 6\times$ ($10^9$–$10^{10}$) cm$^{-2}$. The cross section for $^{16}$O(p, p'$\gamma_{6.129}$)$^{16}$O was taken from Figure 7 of [16]. It reaches $\sim$ 100 mb at $\geq$ 10 MeV. The $^{16}$O($\alpha$, $\alpha$'$\gamma_{6.129}$)$^{16}$O cross section peaks at an $\sim 4\times$ lower energy, so the $\alpha$ contribution can also be significant. Integrating the SEP energy spectrum through the $^{16}$O column, we find an 6.13 MeV line intensity of $\sim 10^{-6}$ to $10^{-5}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at 1 AU.

## Backgrounds and Detection Prospects

The $\gamma$-ray line emission generated by SEP interactions with circumsolar dust will be observed against background continuum emission from two sources. The diffuse Galactic background, attributed to cosmic-ray (CR) electron bremsstrahlung and inverse-Compton (IC) emission, has been modeled by [29] with measurements from the COMPTEL instrument on $CGRO$. Figure 1 shows their intensity spectrum of the inner Galaxy, where the background is highest. At 6.1 MeV that intensity is $\sim$ $2\times10^{-4}$cm$^{-2}$s$^{-1}$sr$^{-1}$. Away from the Galactic center we can expect as much as an order of magnitude decrease in that intensity (figures 2 and 7 of [**?**]). A second background emission source is produced by IC scattering of solar optical photons by Galactic CR electrons and has been calculated by [23, 25]. Their results depend on the assumed modulated CR electron energy spectrum, but the IC emission is a diffuse continuum source with a broad angular distribution peaked in the solar direction. Figure 2 shows differential IC intensities for different solar elongation angles and electron modulation potentials. At 6.1 MeV and 5 deg longitude an upper limit for the differential intensity of IC emission from scattering of solar photons by Galactic CR electrons is $\sim10^{-5}$cm$^{-2}$s$^{-1}$sr$^{-1}$.

As a first step to estimate the heliospheric $\gamma$-ray emission expected from the interaction of intense

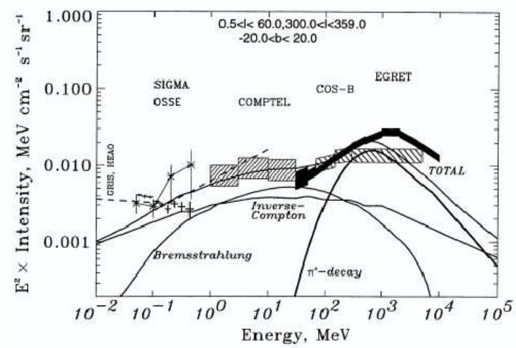


Figure 1: $\gamma$-ray intensity spectrum of the inner Galaxy (from [29]). Observations from $CGRO$ are shown with modeled contributions from the emission processes.

populations of gradual SEPs with circumsolar dust, we have calculated the intensity of the relatively strong O$^{16}$ 6.1 MeV emission line. We used proton and alpha spectra determined for the peaks of the 28 October 2003 and 20 January 2005 GeV SEP events for optimum intensities. Assumptions about the dust composition and spatial density distribution were necessary. We have not considered the expected intensities of other strong $\gamma$-ray lines, neutrons, or the 2.22 MeV neutron-capture line. With the Sun located away from the Galactic plane the low intensities of the extragalactic $\gamma$-ray background continuum above 30 MeV [30] might allow observation of pion decay emission initiated by SEPs of E $>$ 300 MeV in GLE events.

We assume here circumsolar observations extending from $\sim$ 5 to 15 Rs or within about 4$^o$ of Sun center. Our calculated 6.13 MeV line intensities of $\sim 10^{-6}$ to $10^{-5}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for a $10$ MeV proton flux of $10^{10}$ cm$^{-2}$ s$^{-1}$ are $0.5$ to 5 percent the galactic diffuse background. We note two further considerations favorable for detection of a circumsolar SEP-dust $\gamma$-ray detection. First, a transient signal much weaker than a very steady background can be detected with a sufficiently large detector. An excellent example of this is the detection of interplanetary CMEs about two orders of magnitude fainter than the zodiacal light background with the SMEI instrument [12]. Second, passages of sungrazing comets [3, 21, 4] produce locally enhanced dust densities in the 5-15 Rs region, which would increase the target $^{16}$O abundances in the SEP-dust interactions for short periods.

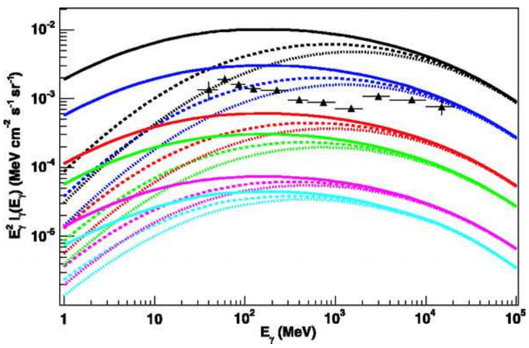

Figure 2: Differential intensities of IC emission from scattering of solar photons by cosmic-ray electrons for selected solar elongation angles ranging from $0.3^o$ (top line sets) to $180^o$ (bottom line sets) from [23]. Solid, dashed, and dotted lines are different assumed CR electron modulation potentials. Data points are diffuse extragalactic $\gamma$-ray intensities.

## Conclusions

We calculate 6.13 MeV line intensities of $\sim 10^{-6}$ to $10^{-5}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for a $10$ MeV proton flux of $10^{10}$ cm$^{-2}$ s$^{-1}$ are $0.5$ to 5 percent the galactic diffuse background. Such a signal might be detectable above the steady Galactic background signal. This could provide a new tool for study of populations of interplanetary SEP events.

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