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Solar Gamma-Ray Science with the EPI-HI/HET Telescope on the Parker Solar Probe

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The High-Energy Telescope (HET) for the EPI-Hi instrument on Parker Solar Probe (PSP) is designed to measure solar energetic-particle (SEP), interplanetary, and galactic cosmic-ray (CGR) ions with 1≤Z≤30 from ~10 MeV/nuc to several hundred MeV/nuc, and electrons from ~0.5 to ~8 MeV. HET also includes a 'neutral-particle' coincidence mode designed to assess the fraction of electron-like events due to γ-rays that Compton scatter or pair- produce in the telescope. Based on γ-ray observations by SMM, RHESSI and Fermi, along with laboratory calibrations with radioactive γ-ray sources, we believe HET is capable of detecting solar γ-ray flares, especially when PSP is close to the Sun. This paper illustrates how HET detects solar γ-rays and presents "quiet-time background" γ-ray spectra (due mainly to γ-rays produced by cosmic-ray interactions in surrounding spacecraft material). The estimated γ-ray yield from the October 28, 2003 events is used as an example of the HET sensitivity.

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1. Introduction

Lingenfelter and Ramaty [1] predicted that energetic nuclei produced in solar flares would collide with the solar surface and produce various γ-ray lines. This was first confirmed by Chupp et al. [2] who observed 4 lines (0.51 MeV from positron annihilation, 2.22 MeV from neutron-proton capture, and 4.4 and 6.2 MeV lines from excited levels in ^{12}C and ^{16}O). Since that OSO-7 discovery the Solar Maximum Mission (SMM), Compton Gamma-Ray Observatory (CGRO), INTEGRAL, RHESSI, and Fermi have observed γ-ray lines and continuum radiation from thousands of solar flares.

After Lingenfelter et al. [3] predicted that solar flares produce neutrons observable at Earth, they were observed by Chupp et al. [4] and have been measured directly by GCRO, SMM, and others. Most solar flare neutrons decay well inside 1-AU and Evenson et al. [5] first observed neutron-decay protons near Earth.

Two recent investigations highlight the importance of measuring γ-ray emission close to the Sun. Feldman et al. [6] describe Messenger measurements of low-energy neutron intensities near Mercury that they attribute to nuclear reactions in the solar atmosphere (see also Lawrence et al. [7,8].) According to Share et al. [9] the Messenger fluxes are 1-2 orders of magnitude greater than predicted by theoretical models and they imply numbers of energetic protons interacting in the solar atmosphere 1-2 orders of magnitude greater than derived from Earth-based γ-ray data from SMM, CGRO, INTEGRAL, RHESSI, and Fermi.

For example, the largest 2.2 MeV γ-ray fluence reported by RHESSI (the 10/28,/2003, X17 event) required 10^{33} >30 MeV protons interacting in the solar atmosphere (Shih et al. 2009 [10]). The number of interacting >30 MeV protons required to explain the Messenger results (for a smaller sample of X-ray flares) ranged from 2 x 10^{33} to ~$10^{35.)}$ (See the last column of Table 3 in Feldman et al [6]).

Share et al. [9] cataloged thirty >100 MeV proton events with sustained (up to >24 hr. duration) solar γ-ray emission (SGRE) observed by Fermi/LAT. They propose that sub-MeV to MeV protons escaping the flare contribute to a seed population that is accelerated by shocks on open field lines to produce SEPs and onto field lines returning to the Sun to produce SGRE. However, deNolfo et al. [11] examined the 1-AU spectra of solar protons up to 500 MeV with PAMELA, STEREO, and GOES data during the SGRE events identified by Share et al. [8]. They found no correlation of proton fluences at 1 AU and the proton fluences needed to produce SGRE γ-rays, and concluded that back-precipitation of CME shock-accelerated protons is not the main source of SGRE emissions.

A second possible source of long duration γ-ray emissions is a model by Ryan and Lee [12] in which protons are accelerated by 2nd-order Fermi acceleration and trapped in extended coronal loops, from which they diffuse into the photosphere, and produce γ-ray emission.

The EPI-Hi instrument on PSP [13] is ideal for investigating the origin of long duration γ-ray events when it is close to the Sun because it can measure both the high-energy solar energetic particle (SEP) environment and any related γ-ray emission. EPI-Hi can also investigate the origin of the anomalously high neutron fluxes reported by Messenger [6,7,8], since the nuclear reactions that produce energetic neutrons also produce γ-ray emission. We start by discussing the heritage for these measurements, which began with the Caltech Electron/Isotope spectrometers on IMP-7&8. See Figure 1.

2. Neutral Particle Detection in Silicon Detectors

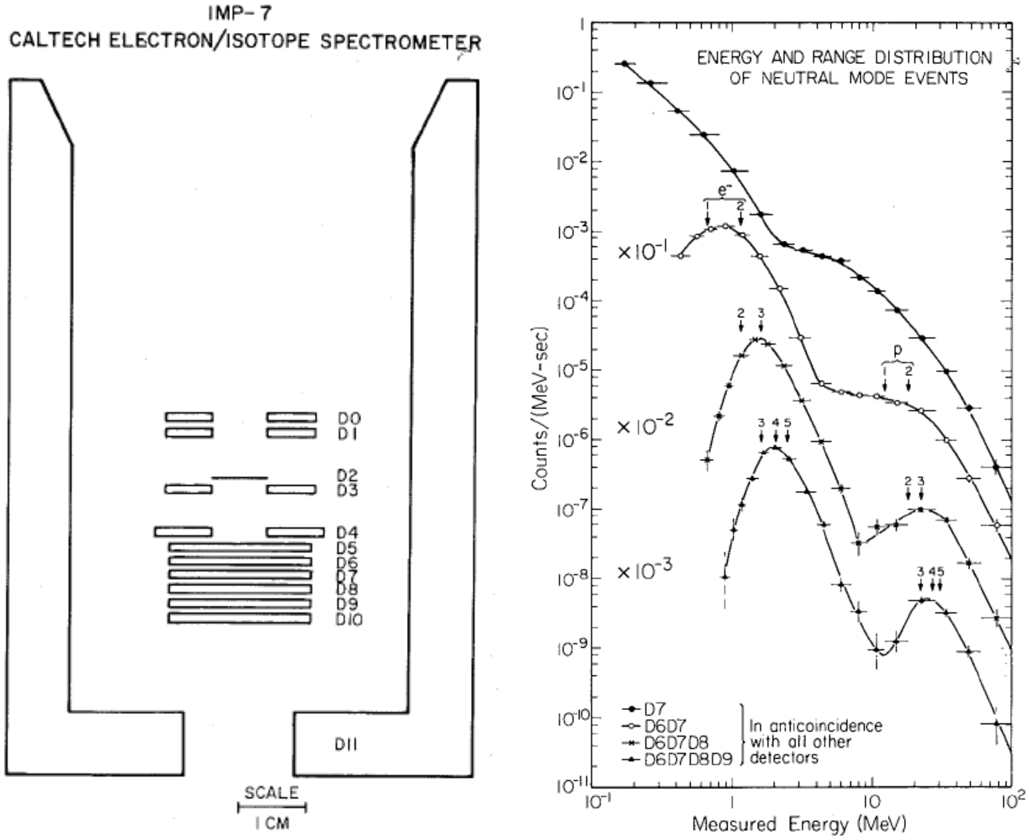

Figure 1a (left): An outline of the EIS telescope on IMP-7. All detectors are 1-mm thick except the 50-μm thick D2. The D5 through D10 detectors all have 1.05 cm^2 active area. A plastic scintillator anti-coincidence cup surrounds most of the telescope. D6 thru D9 make up the neutral mode, triggered by D7. **Figure 1b (right):** Energy-loss distributions of neutral mode events triggered by (from top to bottom) D7 only; D6•D7; D6•D7•D8, and D6•D7•D8•D9 (Mewaldt et al. 2017). The D7•D8 and D7•D8•D9 distributions are essentially identical to D6•7 and D6•D7•D8.

The Caltech EIS instruments on IMP-7 and IMP-8 (Figure 1A) had a Neutral Mode triggered by a 1-mm thick silicon detector (D7) that was completely shielded by a plastic scintillator anti-coincidence cup, by overlying detectors, and by D10. When D7 was triggered (in the absence of all but D6, D8, or D9) the signals from D6, D7, D8, and D9 were summed and recorded. This mode was designed to monitor γ–ray and neutron induced background for (a) quiet-time measurements of interplanetary electrons, and (b) for electrons in SEP events, when the γ–ray background was greater due to nuclear reactions of SEP ions with spacecraft and instrument materials, and due to bremstrahlung from SEP electrons. It is also possible suspected that neutron interactions can produce background for measurements of H and He.

At the very quietest times ~50% of the electron triggers were found to be due to γ-rays made by cosmic-ray interactions with the spacecraft. At more elevated intensity levels the background level increased, but it was a considerably smaller fraction of the (real) electron signal. The background was better correlated with SEP electron intensities than with SEP proton intensities, suggesting that bremstrahlung production in surrounding spacecraft and instrument material was an important contributor. The prelaunch calibration data allowed the contribution of γ-ray interactions to the electron mode to be identified and subtracted (Hurford et al. [14] and Mewaldt et al. [15,16, 17, 18].

Arrows point to the mean energy losses of electrons and protons penetrating 1, 2, 3, and 4 of the 1-mm thick D6-D9 silicon detectors at normal incidence. For each detector combination there is a low-energy peak due to γ-ray interactions (Compton scattering and pair production). The higher energy peaks are due to (n,p), (n,α), and elastic scattering of neutrons in silicon. This was verified by laboratory calibrations with selected β-sources and Pu-Be and Cf-252 neutron sources. Neutron-induced reactions include the following reactions: $^{28}Si(n,p)^{28}Al$, $^{28}Si(n,\alpha)^{25}Mg$, and $^{29}Si(n,\alpha)^{26}Mg$. $^{29}Si(n,\alpha)^{26}Mg$.

This paper describes how γ-rays are measured in the HET instrument, shown in Figure 2. We then provide an example of the estimated number of γ-ray events HET would have measured in the large solar γ-ray flare We then provide an example of the estimated number of γ-ray events that HET would have measured in the large solar gamma-ray flare that was measured by RHESSI on October 28, 2003. With a combination of SEP and γ-ray measurements from the LET and HET sensors on EPI-Hi [13] we can help identify the source of the puzzling observations described above.

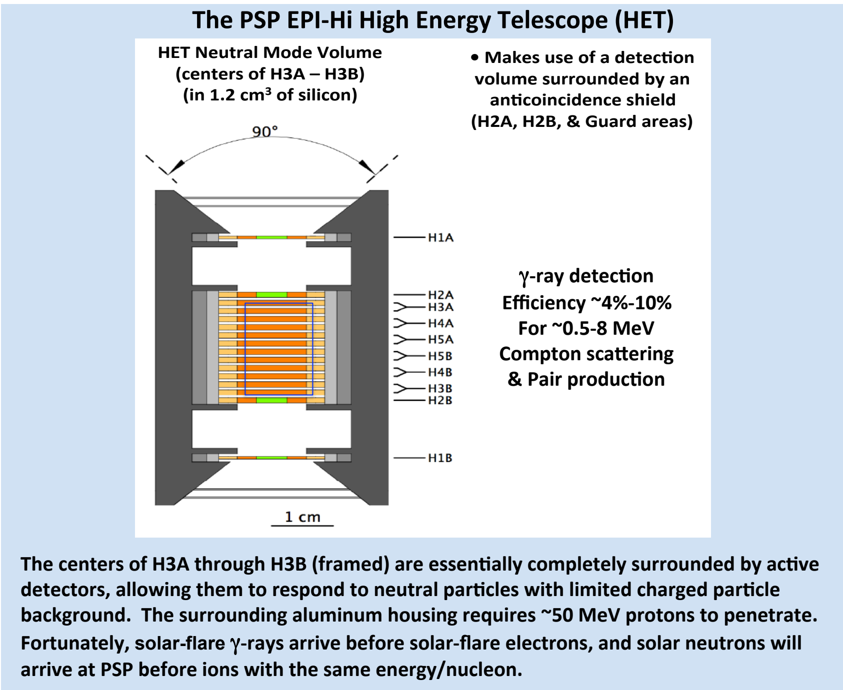

Figure 2: Drawing of the PSP EPI-HET Telescope, explaining the HET Neutral Mode.

3 The EPI-Hi/HET Telescope

The EPI-Hi/HET Telescope (see Figure [2]) is composed of a stack of 16 silicon solid-state detectors including 36 separate segments that combine to measure the trajectory and energy-deposit profiles of incident ions and electrons. The centers of H3A through H3B are essentially completely surrounded by active detectors, allowing them to respond to neutral particles with limited charged particle background (McComas et al. [13]). The surrounding aluminum housing requires ~50 MeV protons to penetrate. Particles that do penetrate are vetoed by the detector guard regions.

4 Response to a Large Solar γ-Ray Flare

Figure 5 shows RHESSI measurements from the October 28, 2003 solar gamma-ray event, the largest of the "Halloween" events (Murphy, 2018). The HET energy-range over which γ-rays can be measured is indicated, as are two of the prominent lines.

Ron Murphy provided the details of the spectrum, which were folded through the HET response, including Compton and pair production reactions in silicon. Attenuation in the TPS was calculated assuming that PSP was aimed directly at the Sun. To be conservative, it was assumed that PSP was at the radius of Venus. The estimated event yield is shown in Figure 7. As for this cycle, to date there have been at most C-class flares since EPI-Hi was turned on.

Fortunately, solar-flare γ-rays arrive before solar-flare electrons and ions, because they travel faster than spiraling electrons or ions. In addition, they do not follow the Parker spiral and are not subject to pitch-angle scattering.

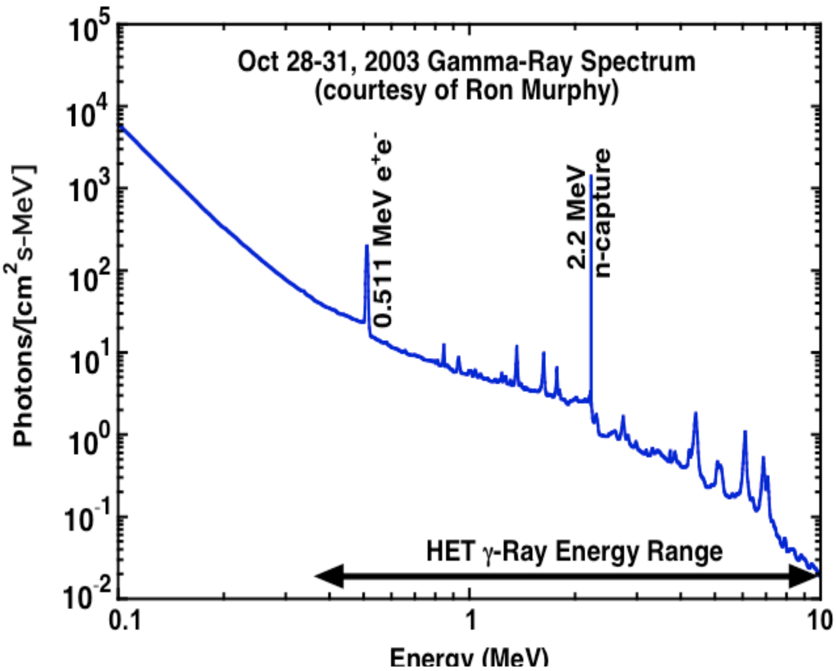

Figure 3: RHESSI γ-ray spectrum measured over October 28-31 following the October 28, 2003 X17 solar flare (the largest of cycle 23.) These data were provided by Ron Murphy of NRL. The prominent lines are indicated. Also shown is the HET energy range for detecting gamma-rays.

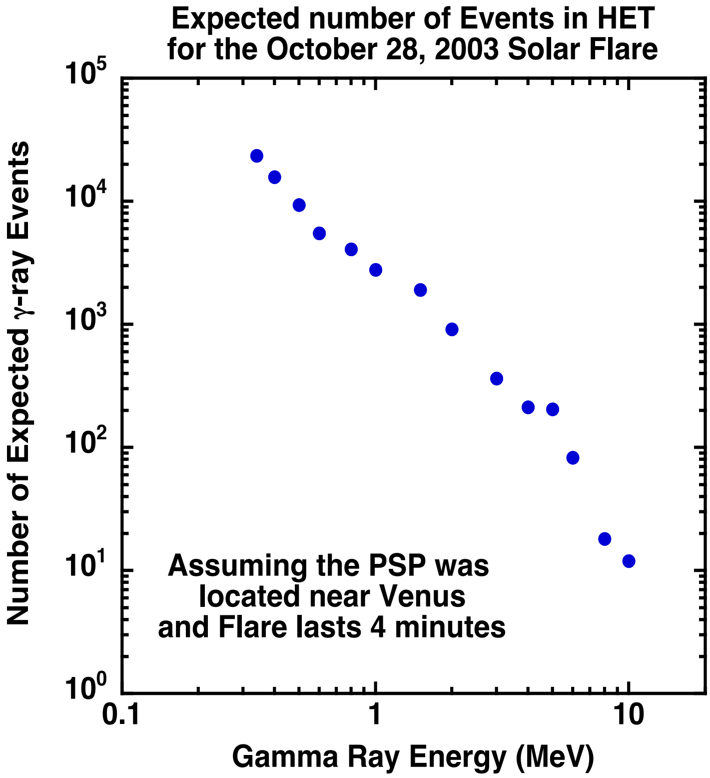

Figure 4: Shown above are the expected number of events that the October 28 flare would have produced in HET. It was surprising to see that in a 4-minute flare HET could potentially analyze ~20,000 gamma-ray events. Of course this was the largest flare of the cycle, but PSP is also assumed to be at its maximum distance once it makes the final pass by Venus. It is also advantageous that all of the □-rays arrive before any of the energetic particles, which avoids background due to SEP interactions with the TPS, spacecraft, and instruments.

Shih et al. [10] used the 2.2 MeV neutron-capture line to estimate the number of >30 MeV protons required to produce the γ-ray emission in 26 Cycle-23 flares. He found Np (>30 MeV) ranged from ~3 x 10^{28} to ~1 x 10^{33}. Once cross-calibrated against data from Fermi for some flares observed in common with Fermi, Solar Orbiter, or any other gamma-ray instrument, HET would be able to make independent estimates of flare magnitudes for flare events observed only by PSP.

In summary, conclude that PSP can make a valuable contribution to solar flare studies by helping to relate in situ SEP data to possible sources and acceleration processes when close to the Sun, especially on the backside when there are no observations from Earth. Near-sun γ-ray measurements should also help solve the origin of sustained γ-ray events (SGRE). Finally, PSP gamma-ray data provide a cross-check on reported Messenger neutron data that appear to require flare emissions 1 to 2 orders of magnitude greater than indicated by other indices.

Summary

We conclude that PSP can make a valuable contribution to solar flare studies by helping to relate in situ SEP data to possible sources and acceleration processes when close to the Sun, especially on the backside when there are no observations from Earth. Near-sun γ-ray measurements should also help solve the origin of sustained γ-ray events (SGRE). Finally, PSP gamma-ray data provide a cross-check on reported Messenger neutron data that appear to require flare emissions 1 to 2 orders of magnitude greater than indicated by other indices.

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References:
[1] R. E. Lingenfelter and R. Ramaty, in High Energy Nuclear Reactions in Astrophysics, Benjamin, p. 99, (1967).
[2] E. L. Chupp, D. J. Forest, P. R. Higbe, A. N. Suri, C. Tsai, and P. P. Dunphy, Nature, 241, 333, 1973.
[3] R.E. Lingenfelter , E. J. Flamm, E. H. Canfield, and S.Kellman , JGR 70, 4087 (1965).
[4] E. L. Chupp. D. J. Forrest, J. M. Ryan, J. Heslin, C. Reppin, C. Pinkau, K. Kanbach, G. Rieger, and G. H. Share , Ap. J. Letters 263. L95, 1982 [5] Evenson, P. Meyer, K.R. Pyle, ApJ 274, 875 (1983).
[5] P. Evenson, P. Meyer, K. R. Pyle, ApJ 274, 875 (1983).
[6] W. C. Feldman, et al., JGR 120, 8247, (2015).
[7] D. J. Lawrence, W. C. Feldman, P. N. Peplowski, and S. C. Solomon, Geophysical Research 120, 5284 (2015a).
[8] D. J. Lawrence, W. C. Feldman, P. N. Peplowski, and S. C. Solomon (2015), J. Geophysical. Research. Space Physics, 120, 5284 (2015b).
[9] G. Share et al., arXiv:1711.01511v1 [astro-ph.SR] 5 Nov (2017).
[10] AY. Shih. R.P. Lin, and D. R. Smith, Ap.J. 698, L152, 2009).
[11] G. A. de Nolfo, A. Bruno, J. M. Ryan, S. Dalla, J. Giacalone, I. G. Richardson, E. R. Christian, W. C. Feldman, S. J. Stochaj, G. A. Basilevskaya, M. Boezio, M. Martucci, V. V. Mikhailov, and R. Munini, accepted for publication in ApJ. (2019).
[12] J. M. Ryan and M. A. Lee, ApJ 368, 316 (991).
[13] D. J. McComas ·N. Alexander, N. Angold, S. Bale, C. Beebe, B. Birdwell, M. Boyle, J.M. Burgum, J. A. Burnham, E. R. Christian, W. R. Cook, S. A. Cooper, A. C. Cummings, A. J. Davis · M. I. Desai, J. Dickinson, G. Dirks, D. H. Do, N. Fox, J. Giacalone, R. E. Gold, R. S. Gurnee, J. R. Hayes, M. E. Hill, J. C. Kasper, B. Kecman, J. Klemic, S. M. Krimigis, A.W. Labrador, R.S. Layman, R. A. Leske, S. Livi, W. H. Matthaeus ·R. L. McNutt Jr, R. A. Mewaldt, D. G. Mitchell, K. S. Nelson, C. Parker, J. S. Rankin, E. C. Roelof, N. A. Schwadron, H. Seifert, S. Shuman, M. R. Stokes, E. C. Stone, J. D. Vandegriff, M. Velli, T. T. von Rosenvinge, S. E. Weidner, M. E. Wiedenbeck, and P. Wilson IV, Space Science Reviews, 204, 187 (2016).
[14] G. J. Hurford, R. A. Mewaldt, E. C. Stone, and R. E. Vogt, Proceedings of the 13th International Cosmic Ray Conference, Denver, 1, 324 (1973).

[15] G. J. Hurford, R. A. Mewaldt, E. C. Stone, and R. E. Vogt, Astrophysical Journal 192, 541 (1974).
[16] R. P. Lin, R. A. Mewaldt, and M. A. I. Van Hollebeke, Astrophysical Journal, 253, 949 (1982).
[17] R.A. Mewaldt, E.C. Stone, and R.E. Vogt, Journalof Geophys. Research,1,2397 (1976).
[18] R.A. Mewaldt, E. C. Stone, and R. E. Vogt, Space Science Instrumentation, 3, 231 (1977)

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