Gamma-Ray Observations with CALET: Exposure Map, Response Functions, and Simulated Results

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The CALorimetric Electron Telescope (CALET) is a space-borne cosmic ray instrument planned for installation on the JEM-EF platform on the International Space Station (ISS) in 2015. The CALET collaboration is a Japan-led international team involving researchers in Italy and the U.S. In addition to precise measurement of the cosmic ray electron and nuclei spectra, the CALET calorimeter will be capable of gamma-ray observations in the energy range 10 GeV - 10 TeV. This paper presents a study of the expected gamma-ray signal measured by CALET in the first year on orbit. The ISS zenith pointing is simulated at a time resolution of 1 second in order to estimate the exposure map on the sky. The instrument response functions and simulated results of gamma-ray/electron separation for the calorimeter are discussed and used to estimate the expected point source and galactic diffuse signals in the energy range 10 GeV - 500 GeV based on known fluxes measured by Fermi-LAT.

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1. Introduction

The CALorimetric Electron Telescope (CALET), a Japanese-led cosmic-ray experiment with Italian and US collaborators, is scheduled for deployment on the International Space Station (ISS) in late 2015 for high-accuracy measurement of electrons above 10 GeV and up to and beyond 10 TeV, as well as protons, heavier nuclei, and gamma-rays [1].

This paper examines the expected gamma-ray signal in CALET after 1 year of on-orbit data collection. An algorithm is developed and evaluated for the separation of a gamma-ray event dataset from the electron dataset based on simulations performed with the EPICS and Cosmos Monte Carlo code [2]. An exposure map is generated for the 1-year CALET orbit on the ISS and presented along with the resulting expectations of gamma-ray counts. Source fluxes and background modelling are based upon recent Fermi-LAT results.

2. The CALET calorimeter

The CALET CALorimeter (CAL) is the primary detector on the CALET mission. It is composed of three main components: the CHarge Detector (CHD), the IMaging Calorimeter (IMC), and the Total AbSorption Calorimeter (TASC). The CHD is composed of two crossed layers of plastic scintillator strips with the purpose of measuring the ionization energy deposit of primary particles entering the CAL. The IMC is eight layers, each made up of a pair of crossed layers of 1mm² plastic scintillator fibers. Interspersed between the eight layers are thin sheets of tungsten. The IMC will be capable of detailed measurement of the early shower development for high-precision reconstruction of the primary particle trajectory. The TASC contains 12 layers of PWO logs alternating in x-/y-orientation, which will absorb the majority of the energy deposited by particle showers [1]. A schematic of the CAL is shown in Figure 1 without the shielding that is present in the Monte Carlo simulations.

3. Gamma-ray/electron separation

Distinguishing between primary electrons and photons will be necessary for any CALET gamma-ray science goals. The algorithm developed and described in this section is based on the signal in those CHD strips which were directly passed through by the primary particle, henceforth referred to as "hit" components. The data used for the following results are generated by the EPICS and Cosmos Monte Carlo simulation package on the LSU High Performance Computing SuperMike-II cluster.

Gamma-ray and electron events were generated isotropically on a partial sphere (θ ≤ 110°) with an E⁻¹ spectrum in three energy bins: 10-100 GeV, 100-1000 GeV, 1-10 TeV. Events were generated for each species in each of these energy bins and subsequently filtered based on their trajectories. The requirements placed on events for analysis follow the "type B" geometry as defined in [3]. Explicitly, this enforces that the primary particle pass through both the top of the CHD and the bottom of the TASC. Numbers of events in each energy bin are summarised in Table 1.

For each of the type B events, the energy deposits in the hit strips in CHDx and CHDy were summed, respectively. Histograms of these deposits (see Figure 2 and Figure 3) verify that the
distribution for electrons appears as a minimum ionizing particle (MIP) distribution. Some gamma-rays pair produce in the aluminium structure above the detector or in the CHD itself, leading to partial energy deposits due to secondary electrons and a feature around 4 MeV (2 MIP) clearly seen in the 10-100 GeV and 100-1000 GeV histograms. The pair production cross section increases with photon energy, leading to an increasing fraction of non-zero energy deposits in the CHD at higher energies. In the 1-10 TeV histogram, the 4 MeV feature is indistinguishable from the continuum due to the large fraction of gamma-rays which interact above and within the CHD.

Scatter plots showing the total energy deposited in the hit components of CHDy as a function of the total energy deposited in the hit components of CHDx provide a graphical representation of the cuts used to separate the gamma-rays from the electrons. As can be seen in Figure 4, two straight lines (one nearly horizontal, the other nearly vertical) can be drawn which largely divide the samples. The functional requirement for identifying a gamma-ray by this scheme can be written

\[ \text{CHD}_x \text{dE} \leq 0.09 \times (\text{CHD}_y \text{dE} + 0.01) \quad \text{or} \quad \text{CHD}_x \text{dE} \geq (\text{CHD}_y \text{dE}/0.09) - 0.01 \] (3.1)

The criterion in Eq. 3.1 was applied to all of the type B events in order to characterize the loss of gamma-rays from the sample and the rejection of electrons. The statistical results are summarised in Table 2.

### Table 1: Statistics for electron and gamma-ray events generated in EPICS

<table>
<thead>
<tr>
<th>Species</th>
<th>Energy</th>
<th># Generated</th>
<th># in Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-</td>
<td>10-100 GeV</td>
<td>2,000,896</td>
<td>7675</td>
</tr>
<tr>
<td></td>
<td>100-1000 GeV</td>
<td>2,000,896</td>
<td>7554</td>
</tr>
<tr>
<td></td>
<td>1-10 TeV</td>
<td>2,000,896</td>
<td>7485</td>
</tr>
<tr>
<td>γ</td>
<td>10-100 GeV</td>
<td>2,000,896</td>
<td>7482</td>
</tr>
<tr>
<td></td>
<td>100-1000 GeV</td>
<td>2,000,896</td>
<td>7649</td>
</tr>
<tr>
<td></td>
<td>1-10 TeV</td>
<td>2,000,896</td>
<td>7573</td>
</tr>
</tbody>
</table>

### Table 2: Efficiency for separation of electrons and gamma-rays in type B geometry into individual datasets

<table>
<thead>
<tr>
<th>Species</th>
<th>Energy</th>
<th># ID as γ</th>
<th>% ID as γ</th>
<th># ID as e</th>
<th>% ID as e</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-</td>
<td>10-100 GeV</td>
<td>8</td>
<td>0.104%</td>
<td>7667</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>100-1000 GeV</td>
<td>5</td>
<td>0.0662%</td>
<td>7549</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>1-10 TeV</td>
<td>5</td>
<td>0.0668%</td>
<td>7480</td>
<td>99.9%</td>
</tr>
<tr>
<td>γ</td>
<td>10-100 GeV</td>
<td>7217</td>
<td>96.5%</td>
<td>265</td>
<td>3.54%</td>
</tr>
<tr>
<td></td>
<td>100-1000 GeV</td>
<td>7275</td>
<td>95.1%</td>
<td>374</td>
<td>4.89%</td>
</tr>
<tr>
<td></td>
<td>1-10 TeV</td>
<td>5797</td>
<td>76.5%</td>
<td>1776</td>
<td>23.5%</td>
</tr>
</tbody>
</table>

4. CALET 1-year exposure map

When deployed on the ISS, CALET will always be oriented toward the zenith [3]. It has a 45° field of view radius and a high orbital inclination, and will, as such, be an all-sky monitor of
high-energy gamma-rays. In order to estimate the number of photons from known sources (diffuse galactic emission, isotropic emission, and persistent point sources), a map of exposure time on the sky has been generated. The resolution of the sky map was chosen to match the Fermi-LAT galactic diffuse background model \( [4] \), which is binned to \( 0.125^\circ \times 0.125^\circ \) in galactic coordinates. Orbital ephemeris information was generated for the ISS orbit for a full year at 1s resolution using the AGI Satellite Toolkit (STK) software. The calculated pointing directions were transformed to galactic coordinates and used to determine the total duration for which each bin on the sky would be within the field of view of the instrument. The resulting exposure map is shown in Figure 5.

5. Estimated number of events

The fluxes given in the Fermi-LAT models have units of \( [\Phi] = \text{photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1} \). To calculate the number of photons incident on the instrument, the following expression was used

\[
N = \Phi \times A_{\text{eff}} \times t_{\text{exp}} \times \Omega_{\text{bin}} \times \Delta E_{\text{bin}}
\]  

(5.1)

The effective area \( A_{\text{eff}} \) is given as a function of event geometry in Figure 3 of \([3]\). The value for type B geometry is not available, so the value of 500 cm\(^2\) for the more restrictive type A geometry is used to provide a lower bound. The exposure time \( t_{\text{exp}} \) is taken for each bin from the generated exposure map in Figure 5. The solid angle of the each sky bin can be calculated as a function of the bin center galactic latitude (\( b_c \)) with the integral

\[
\Omega_{\text{bin}} = \frac{0.125^\circ \times \pi}{180^\circ} \int_{b_c + 90^\circ + 0.0625^\circ}^{b_c + 90^\circ - 0.0625^\circ} d\theta \sin(\theta)
\]  

(5.2)

with the exception of the bins at \( \pm 90^\circ \), which have a slightly different size:

\[
\Omega_{\text{bin}} = \frac{0.125^\circ \times \pi}{180^\circ} \int_{0^\circ}^{0.0625^\circ} d\theta \sin(\theta)
\]  

(5.3)

The energy bin sizes (\( \Delta E_{\text{bin}} \)) are logarithmically spaced and vary based on the Fermi-LAT model being considered.

5.1 Diffuse galactic and isotropic

The Fermi-LAT background models \([4]\) give fluxes for the isotropic and galactic diffuse gamma-ray signals. Since the energies are binned differently for the two models and the background spectra are not within the scope of this paper, the contributions from all energy bins above 10 GeV (reaching up to 500 GeV for galactic sources and up to 600 GeV for the isotropic signal) are summed to obtain a total number of background photons in each sky bin. Summing the contributions from every sky bin, we calculate that CALET will be exposed to more than 3500 in-geometry photons from the known diffuse flux per year.

5.2 Persistent sources

The estimate of counts from point sources was taken from the first Fermi-LAT catalog of high-energy gamma-ray sources \([5]\). Extended sources which subtend less than 2\(^\circ\) are included in this catalog, while larger extended sources are contained in the diffuse galactic background model \([4]\).
The total number of photons from these sources is calculated to be on the order of 350. A list of the five brightest sources for CALET is provided in Table 3. All sources with more than three incident photons are also shown on a sky map in Figure 6.

### Table 3: The five brightest 1FHL sources detected in one year of CALET orbit.

<table>
<thead>
<tr>
<th>1FHL designation</th>
<th>Common ID</th>
<th>Type</th>
<th># of photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0835.3-4510</td>
<td>Vela</td>
<td>PWN</td>
<td>22</td>
</tr>
<tr>
<td>J0534.5+2201</td>
<td>Crab</td>
<td>PWN</td>
<td>19</td>
</tr>
<tr>
<td>J2028.6+4110e</td>
<td>MGRO J2031+41</td>
<td>N/A</td>
<td>12</td>
</tr>
<tr>
<td>J1104.4+3812</td>
<td>Mkn 421</td>
<td>HBL</td>
<td>11</td>
</tr>
<tr>
<td>J0617.2+2234e</td>
<td>IC443</td>
<td>Shell</td>
<td>8</td>
</tr>
</tbody>
</table>

Note that the sources whose 1FHL designation ends with an 'e' are extended sources. The photons from these sources will be spread across several sky bins. The background in each individual sky bin was calculated, considering both the diffuse gamma-ray emission and the contamination from electrons (flux taken as upper limit of PAMELA results for the 10-600 GeV range [6]), and found to be negligible compared to the signal from these sources.

### 6. Observation of transient systems

The results of section 5 demonstrate that the performance of CALET does not have the capability to contribute to the study of persistent emission from sources possible with Fermi-LAT. The real strength of CALET for high-energy gamma-rays is the large orbital inclination of the ISS and the large field of view. These properties make CALET very well-suited as an all-sky monitor for high-energy flares.

As an example, the expected number of photons was calculated for two historical high-energy Crab flares. The flares will be characterized by their duration ($\tau$) and the ratio of the average flux during the flare to the ambient flux ($\alpha$). For the April 2011 flare, $\tau \approx 10$ days and $\alpha \approx 30$. [7], and for the March 2013 flare, $\tau \approx 20$ [8]. If a flare were to occur on a day where CALET could ideally observe it, the exposure time is approximately 12600 seconds (25% of the full day). The expected signal from an $\alpha = 25$ flare is then $N \approx 2$ photons. For the historical flares, the fractional exposure time is taken to be 16% of the total flare time, which is the ratio of the exposure time calculated for the Crab in the orbit simulation to the total time in one year. These parameters yield an estimate of 15 photons over the full flaring period for either flare. This translates to a 3.8σ excess above the ambient background and typical Crab signals.

A confirmed observation of a flaring system in the CALET energy range would indicate an inverse Compton scattering component in the flare mechanism. To our knowledge, all high energy flaring systems to date have been found to flare via a strong synchrotron enhancement. Studies of these mechanisms in such systems are necessary to progress the understanding of the underlying physics in these high energy flares.
Acknowledgements

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References


Figure 1: Simulation of a 1 TeV electron in the CAL.
Figure 2: Histograms of CHD energy deposits for electrons, summed over hit strips per layer.

Figure 3: Histograms of CHD energy deposits for gammas, summed over hit strips per layer.

Figure 4: Energy deposits in CHDy vs. CHDx for both electrons and gammas in each energy range. The blue lines indicate the cuts made to separate the samples.
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Figure 5: CALET exposure map for continuous observation from Nov. 1, 2015 through Oct. 31, 2016.

Figure 6: 1-year count map for CALET gamma-rays. The background color represents intensity of diffuse emission in the area. The stars are steady point sources, with the size of the marker proportional to the number of photons. Only sources with $\geq 3$ photons are shown on the plot.