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Point-like source catalog observed by DAMPE

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The DArk Matter Particle Explorer (DAMPE) is a high-energy cosmic ray and gamma-ray detector located in space. Over a period of seven years since its launch on December 17, 2015, DAMPE has surveyed the entire sky and collected an extensive dataset of more than 300,000 photons with energies above 2 GeV. To analyze the gamma-ray data obtained by DAMPE, instrument response functions (IRFs) have been derived, and a specialized software called DmpST has been developed. In this context, we present the results of the DAMPE gamma-ray point-like source catalog. This catalog provides valuable information about the detected gamma-ray sources, which includes details such as the positions, energy spectra, and flux measurements of these point-like gamma-ray sources. By studying these sources, scientists can gain insights into various astrophysical phenomena, including the emission processes and distribution of gamma-ray sources in the universe.

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1. Introduction

The DArk Matter Particle Explorer (DAMPE) is a space-borne particle detector designed to study high-energy astrophysics and investigate the properties of dark matter particles[1]. DAMPE comprises four components, as shown in Figure 1, including:

1. Plastic Scintillator Detector (PSD): The PSD is responsible for measuring the charge of incoming particles, particularly it can distinguish electrons and photons.

2. Silicon-Tungsten tracKer-converter (STK): The STK is designed to track the trajectories of charged particles. It consists of layers of silicon microstrips combined with tungsten converters, which help in converting incoming photons into electron-positron pairs for detection.

3. BGO calorimeter (BGO): The BGO calorimeter is used to measure the energy of incoming particles. It is composed of Bismuth Germanate (BGO) crystals that generate scintillation light when interacting with high-energy particles.

4. NeUtron Detector (NUD): The NUD is specifically designed to detect and measure neutrons. It plays a crucial role in distinguishing between different types of particles and helps in reducing background noise in the measurements.

These components work together to detect and measure charged cosmic rays and gamma-rays over a wide energy range. By analyzing the data collected by DAMPE, scientists can gain valuable insights into high-energy astrophysical phenomena and contribute to our understanding of dark matter.

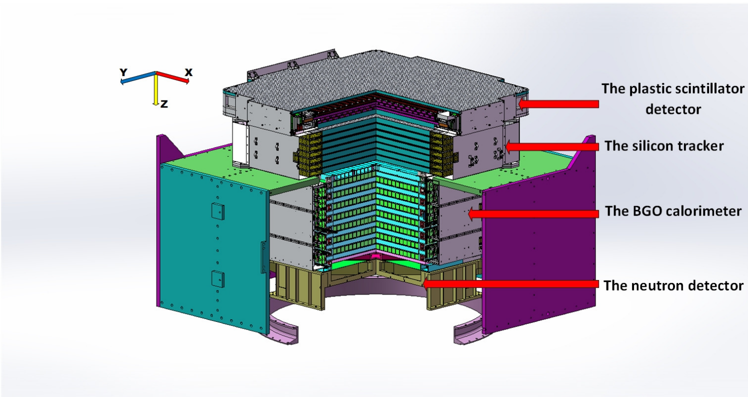

Figure 1: Schematic view of the DAMPE detector[1].

DAMPE is designed to observe gamma rays in the energy range from 2 GeV to 10 TeV. It has an effective area of approximately 1200 cm^2 for normal incident events, which means it can efficiently detect gamma rays within this energy range. The angular resolution of DAMPE is around 0.2 degrees, which means it can determine the direction of incoming gamma rays with a high degree of precision. The energy resolution of DAMPE is about 1% at 100 GeV, which indicates its ability to accurately measure the energy of gamma rays within this energy range. DAMPE is placed in a 500 km solar-synchronous orbit with an inclination of approximately 97 degrees. This orbit ensures a stable and controlled environment for the observations. The spacecraft completes one orbit in about 95 minutes. Since its launch, DAMPE has been undergoing regular calibrations to maintain the accuracy of its data[2]. These calibration procedures are crucial for calibrating the detector response, correcting for instrumental effects, and ensuring the quality and reliability of the observations. The combination of the wide energy range, effective area, angular resolution, and energy resolution, along with the careful calibrations, makes DAMPE a powerful instrument for studying gamma rays and contributing to our understanding of high-energy astrophysics.

2. Gamma-ray data of DAMPE

After over seven years of operation, DAMPE has accumulated a substantial dataset of more than 300,000 gamma-ray events above 2 GeV. These events have been carefully selected from the entirety of DAMPE's detected events using a specific gamma-ray photon selection algorithm [3]. This selection process ensures that the collected gamma-ray events are of high quality and suitable for analysis.

To ensure the accuracy of the gamma-ray data, the calibration of boresight alignment has been performed. This calibration procedure is essential for aligning the instrument's pointing direction with the observed gamma-ray sources, allowing for accurate spatial analysis and source identification [4].

In addition, instrument response functions (IRFs) have been derived for DAMPE's gamma-ray observations. These IRFs describe the instrumental response to incoming gamma rays in terms of energy, angular resolution, and effective area. They are crucial for properly analyzing the gamma-ray data and extracting meaningful scientific results. Furthermore, a dedicated software package called DmpST has been developed specifically for the analysis of DAMPE's gamma-ray data [5]. This software provides tools and functionalities for data processing, calibration and scientific analysis, enabling researchers to extract valuable information from the collected gamma-ray events.

These calibration efforts, along with the development of dedicated analysis software, ensure the accuracy and reliability of the gamma-ray data collected by DAMPE. They facilitate the exploration of high-energy astrophysics and contribute to our understanding of gamma-ray sources and the nature of dark matter particles.

In this work, we focus on analyzing the first 7.2 years' gamma-ray data collected by DAMPE, specifically from 1 Jan. 2016 to 20 Mar. 2023. To ensure the reliability and accuracy of the data, we take certain measures to remove events that may introduce noise or interference.

One of the steps we take is to exclude the events that occurred when DAMPE traveled through the South Atlantic Anomaly (SAA). The SAA is a region of increased radiation around the Earth's South Atlantic region, which can affect the performance of detectors and introduce unwanted signals in the data. By removing events during this time, we aim to mitigate the impact of SAA-related effects on the gamma-ray data.

Additionally, we also exclude events that occurred during solar flare periods. Solar flares are sudden bursts of energy from the Sun that can lead to increased levels of radiation in space. By excluding events during solar flare periods, we minimize the potential influence of these transient events on the gamma-ray data.

By applying these exclusion criteria, we can ensure that the selected gamma-ray data for analysis is free from known sources of interference and provides a cleaner dataset for our research.

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3. Method of blind search for source candidates

In the analysis of the gamma-ray data, it have identified three main components in the data: galactic diffuse emission, resolved sources, and isotropic diffuse emission, as shown in Figure 2.

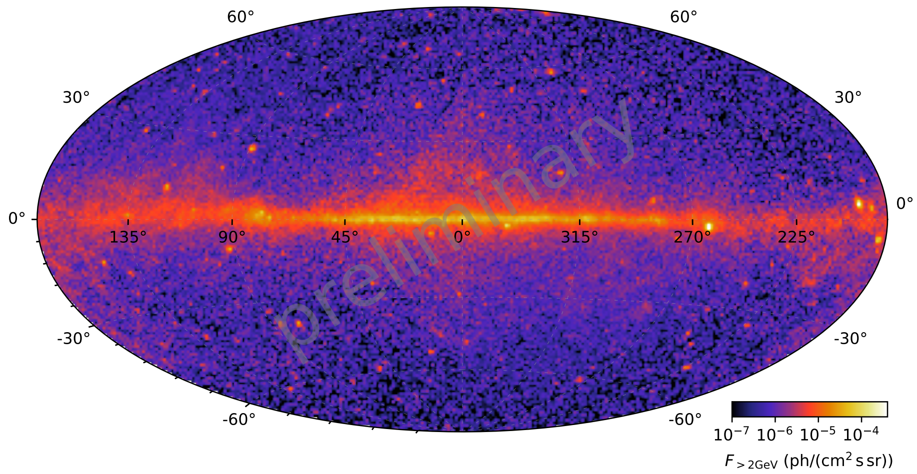

Figure 2: Flux map of DAMPE 7.2 years gamma-ray data in galactic coordinate with Aitoff projection.

To effectively detect resolved sources, we apply the Li-Ma method[6]. The Li-Ma method is a statistical technique commonly used in gamma-ray astronomy to identify significant excesses of gamma-ray events compared to the background. It is particularly useful for blind searches of gamma-ray sources, where the location and characteristics of the sources are not known beforehand. By applying the Li-Ma method, we can identify candidate source regions that show a statistically significant excess of gamma-ray events, indicating the presence of potential gamma-ray sources.

To estimate the expected contribution of galactic diffuse emission, we use a model based on observations from Fermi-LAT (Fermi Large Area Telescope)[7]. Fermi-LAT is a space-based gamma-ray telescope that has extensively studied the galactic diffuse emission, which is the gamma-ray emission coming from various processes within our galaxy. By using the Fermi-LAT model[8], it can estimate the expected background gamma-ray emission from galactic sources, which is essential for distinguishing genuine gamma-ray sources from the diffuse emission.

By combining the Li-Ma method for source detection and the Fermi-LAT model for estimating the galactic diffuse emission, we effectively separate and analyze the resolved sources in your gamma-ray data. This allows us to identify and study potential gamma-ray sources of interest and understand their characteristics and properties.

We divide the data into more than 3 million pixels of equal solid angle using HEALPix[9] projection with N_{side}=512. Each pixel, along with its 8 neighbors, was selected as an "on" region. The angular size of each pixel and the "on" region is 0.1° and 0.3°, respectively. To mitigate the effects of sources and galactic diffuse emission, we employ a two-step process to determine the "off" region. Initially, we select the neighbors with N_{side}=16 for each pixel as the "off" region to obtain the initial significance of the sky. Subsequently, we chose the pixels located at high galactic latitudes (|b|>30°) with a significance level below 2.5 as the final "off" region, yielding the significance map.

Figure 3 displays the significance map of the DAMPE gamma-ray data obtained using the Li-Ma method. This map highlights regions of the sky where the observed gamma-ray events exhibit a significant deviation from the expected background, indicating the presence of potential gamma-ray sources.

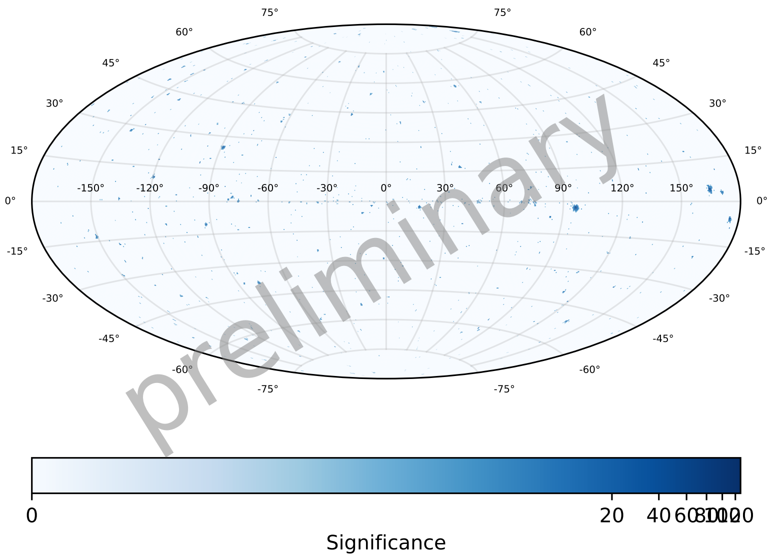

Figure 3: The significance map of DAMPE gamma-ray data obtained using the Li-Ma method.

After selecting the pixels with a significance greater than 3 as source candidates, a total of 2902 candidates have been identified. To further analyze and characterize these candidates, likelihood analyses are performed using the dedicated software DmpST. The likelihood analysis aims to determine the most probable parameters of each candidate source, such as its position, spectral shape, and flux. This analysis takes into account the instrument response functions, background estimation, and statistical uncertainties to obtain reliable results.

4. Detection of gamma-ray sources

To analyze the data around each candidate source, we extract a region of interest (ROI) with a radius of 5 degrees centered on each candidate. Within this ROI, the data is binned into 15 energy bins on a logarithmic scale and spatially binned into bins of 0.05 degrees. For each candidate source, we assume a point source model with a PowerLaw spectrum in its direction. In addition, we consider the galactic diffuse emission model derived from Fermi-LAT's observations and an isotropic diffuse model with a PowerLaw spectrum. By fitting the data within the ROI with these models, we can estimate the likelihood ratio and obtain the Test Statistic (TS) value for the source, given by $TS_{\text{source}} = 2\ln\left(\frac{L_{\text{with PS}}}{L_{\text{without PS}}}\right)$. The TS value measures the significance of the candidate source by comparing the likelihood of the data when including the source model (with PS) to the likelihood when excluding it (without PS). A higher TS value indicates a better fit of the data with the presence of the candidate source. The TS value can be used to assess the statistical significance of the candidate source and guide further analysis and interpretation.

After analyzing the data for each candidate source and calculating the TS values, we find that 595 sources have TS values larger than 20 (TS > 20). These sources meet the criteria for inclusion in the initial catalog. In order to mitigate the impact of nearby sources and improve the accuracy of the analysis, a strategy is employed where the sources within a 10-degree circle around each candidate are included in the model. By incorporating nearby sources into the model, we account for their contribution to the observed gamma-ray data and minimize any potential contamination or overlapping signals. The data is then refit using this updated model, allowing for a more precise determination of the properties and characteristics of the candidate source.

We also fit the data with curved spectra, specifically with the LogParabola model $\frac{dN}{dE} = N_0(E/E_b)^{-\alpha+\beta\log(E/E_b)}$ and the PLSuperExpCutoff model $\frac{dN}{dE} = N_0(E/E_0)^{\gamma}\exp(-(E/E_c)^b)$. This allowed us to obtain the TS value for the curved spectra, denoted as $TS_{\mathrm{cur}} = 2\ln(L_{\mathrm{cur}}/L_{\mathrm{PL}})$. If the value of TS_{cur} is larger than 9, it indicates that the significance of the curved spectrum is greater than 3σ. Our analysis revealed that six sources favored the LogParabola spectrum, while three sources favored the PLSuperExpCutoff spectrum.

After performing the refit of the data by including the nearby sources within a 10-degree circle, a more stringent selection criterion is applied to the sources based on their TS value. In this case, only sources with a TS value greater than 25 are considered for inclusion in the final catalog. The resulting catalog consists of 248 sources that meet this more stringent criterion and are considered as the final sources of interest in the analysis. These sources have exhibited a high level of significance and are expected to represent genuine gamma-ray sources in the observed data.

To determine the types of the sources in the final catalog, they are associated with the Fermi-LAT's 4FGL catalog[10]. The 4FGL catalog is a comprehensive catalog of gamma-ray sources detected by the Fermi-LAT instrument. It provides information about the identified counterparts and the spectral properties of the sources. By cross-matching the positions of the sources in the final catalog with the positions of the sources in the 4FGL catalog, we can establish associations and determine the types of the sources. The association with the 4FGL catalog allows us to classify the sources in the final catalog into different types, such as pulsars, active galactic nuclei (AGNs), supernova remnants (SNRs), and others. The types of the associated sources provide valuable insights into the nature and origin of the gamma-ray emission.

To determine the association of sources observed by DAMPE with sources in the Fermi-LAT's 4FGL catalog, we calculate the angular separations between the positions of the DAMPE sources and the positions of the 4FGL sources. The nearest source in the 4FGL catalog within a certain separation threshold is considered as the association of the DAMPE source. There are four sources that have a separation distance larger than 0.5° between the sources observed by DAMPE and their associations in 4FGL.

Figure 4 provides a visual representation of the types and spatial distribution of the gamma-ray sources observed by DAMPE, offering insights into the diversity and distribution of these sources in the sky. Figure 5 displays the separations distribution between sources observed by DAMPE and thesociations in the 4FGL catalog. Table 1 presents the types of sources observed by DAMPE, along with the corresponding numbers of each type. According to Table 1, DAMPE has observed 175 AGNs, 46 pulsars, 10 SNRs/PWNs, 6 binary systems, and 11 unassociated sources.

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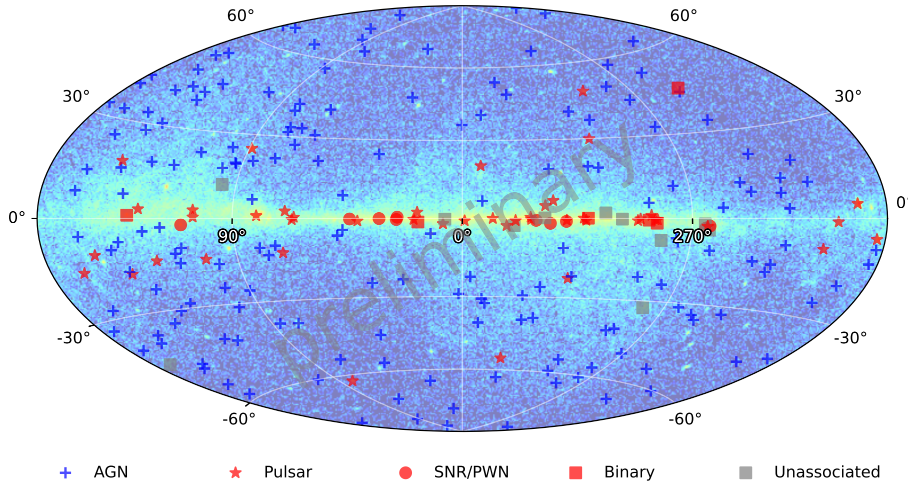

Figure 4: The types and spatial distribution of the gamma-ray sources observed by DAMPE.

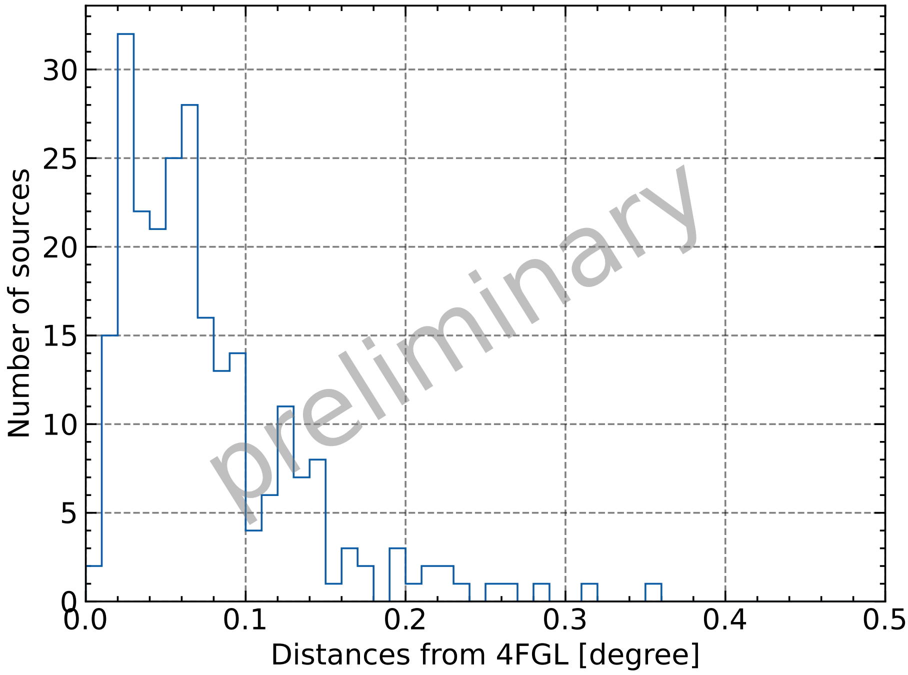

Figure 5: The separations distribution between sources observed by DAMPE and their associations in the 4FGL catalog.

Table 1: The types and corresponding numbers of sources observed by DAMPE.

Type	AGN	Pulsar	SNR/PWN	Binary	Unassociated	Total
Number	175	46	10	6	11	248

5. Summary

After 7.2 years of operation, DAMPE has gathered a substantial dataset, consisting of over 300,000 photons above 2 GeV. Utilizing this dataset, a total of 248 gamma-ray sources have been detected and analyzed by DAMPE. The spectra of these sources have been determined, with the majority of them favoring a PowerLaw spectrum. Additionally, three sources have been found to exhibit curved spectra.

By associating the observed sources with the 4FGL catalog, the types of these sources have been determined. The analysis reveals that a significant portion of the sources are associated with Active Galactic Nuclei (AGNs) and pulsars, indicating their origin in high-energy astrophysical processes associated with these objects.

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