PROCEEDINGS OF SCIENCE

The Solar Flare Catalog with GECAM

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The GECAM (Gravitational Wave High-energy Electromagnetic Counterpart All-sky Monitor) mission has significantly enhanced the detection and analysis of high-energy astrophysical phenomena, particularly solar flares. This study presents a comprehensive catalog of solar flares observed by GECAM, systematically documenting 774 high-energy flare events from January 2021 through December 2024. Through a rigorous three-stage screening process—including spatial filtering (<20° deviation from the solar center), spectral-temporal analysis, and cross-validation with GOES satellite data—we precisely identified and classified flares across different intensity levels. The catalog provides detailed records of flare timing, spatial distribution, energy spectra, and key temporal parameters (e.g., rise time, decay time, and duration). These findings not only validate the critical role of high-energy observations in deciphering solar dynamics but also establish GECAM as an indispensable tool for solar physics and multi-messenger astrophysical research.

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1. Introduction

A solar flare is an extremely violent energy release phenomenon in the Sun's atmosphere, typically accompanied by intense electromagnetic radiation and the acceleration of high-energy particles. The observation and study of flares are of great significance for understanding solar activity, space weather, and stellar physics. The high-energy radiation from flares is mainly concentrated in the X-ray and gamma-ray ranges, with its production closely related to magnetic reconnection processes. Research on solar flares not only helps reveal the internal physical processes of the Sun but also has important applications in space weather forecasting and satellite communications. In recent years, advances in space observation technology have significantly enhanced our understanding of flare temporal evolution and spatial structure through multi-wavelength observations and analysis.

Current research on solar flare catalogs is in a phase of rapid interdisciplinary development. Using collaborative multisatellite observation systems, including GOES, SDO, and RHESSI[1], comprehensive databases covering X-ray, ultraviolet, radio, and other wavelengths have been established. Research focuses on four key areas: at the data level, deep learning algorithms enable automated flare detection and classification, significantly improving the spatiotemporal resolution of GOES flare catalogs; in terms of physical mechanisms, combining SDO/HMI magnetic field observations with RHESSI high-energy particle data allows in-depth investigation of energy release processes during magnetic reconnection, particularly the scaling laws between microflares and standard flares; in applications, efforts focus on building flare-CME correlation models to enhance space weather forecasting capabilities[2], though challenges remain in understanding energy distribution mechanisms and eruption timing causality; technologically, PSP's close-range observations and DKIST's high-resolution imaging are advancing flare cataloging toward subarcsecond structural analysis[3]. While AI-driven multimodal data fusion has made progress, fundamental issues like non-thermal particle acceleration mechanisms and the coupling between magnetic topology evolution and radiation response still require breakthroughs.

This study primarily uses data from the Gravitational Wave High-energy Electromagnetic Counterpart All-sky Monitor (GECAM) for solar flare catalog analysis. The second part introduces GECAM, the third part describes the data, the fourth part presents the results of the analysis, and the last part provides conclusions.

2. GECAM

The discovery of electromagnetic counterparts to gravitational waves marked the advent of the era of multi-messenger astronomy, necessitating high-energy transient detection instruments with all-sky monitoring capabilities. Launched in 2020, the Gravitational Wave High-energy Electromagnetic Counterpart All-sky Monitor (GECAM) satellite was specifically designed to capture short-timescale gamma-ray bursts (GRBs), magnetar outbursts, fast radio burst high-energy emissions, and other transients, leveraging its unique advantages of high sensitivity, rapid response (millisecond level) and coverage of the soft gamma-ray energy range (10 keV–6 MeV). The mission has systematically compiled key parameters (such as time, location, energy spectrum, and light curves) of high-energy transient events including gamma-ray bursts and magnetar outbursts. Its dis-

PoS(ICRC2025)1383

tinctive capability lies in the sensitive detection of short-duration weak signals, filling observational gaps in traditional catalogs (e.g., Fermi/GBM). This catalog not only provides a data foundation for studying compact object mergers and extreme magnetar activities but also advances our understanding of extreme cosmic environments through multi-messenger correlations (e.g. gravitational waves and neutrino events), serving as a vital resource for time-domain astronomy and multi-messenger research.

GECAM consists of two microsatellites [4], designed to achieve comprehensive temporal and spatial monitoring of high-energy electromagnetic counterparts to gravitational waves (ie gravitational wave gamma-ray bursts) [5]. Its payload includes two types of detectors, gamma ray detectors (GRDs) and charged particle detectors (CPDs) —alongng with a payload processor and a main structural assembly[6](as shown in Figure 1).

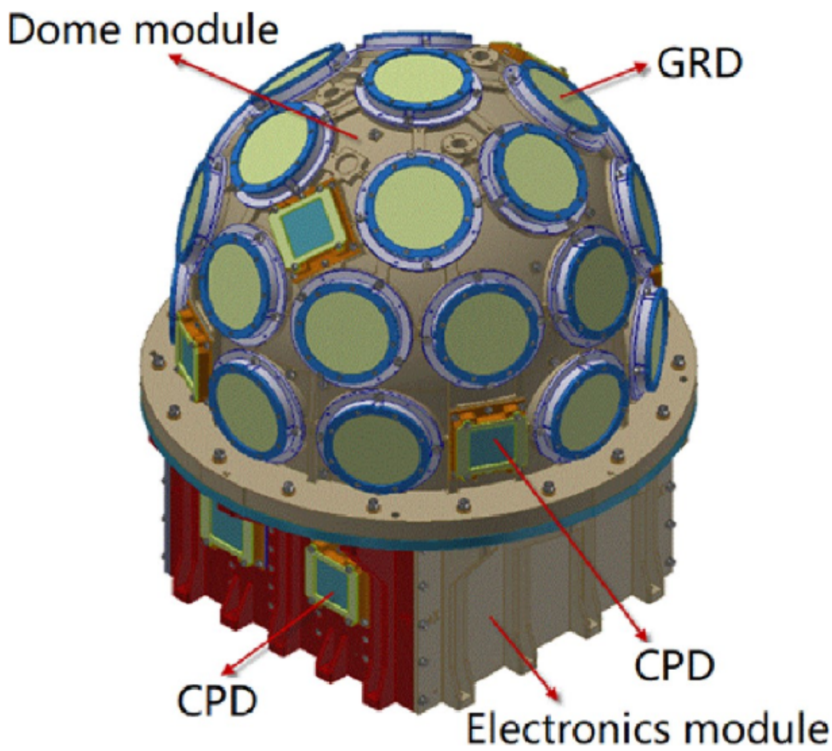


Figure 1: Structure of payloads of GECAM

The GRB detection system comprises three major modules: detectors, data processing, and structural support. (1) The GRD detectors incorporate 25 lanthanum bromide ($LaBr_3$) crystal units [7], covering an energy range of 8 keV–2 MeV to enable GRB light curve/spectral measurements and localization. (2) The CPD detectors consist of eight plastic scintillator units to discriminate against space-borne charged particle interference. (3) The payload processor integrates five data acquisition boards, one data management board, and a power supply board to execute signal processing, trigger decision-making, localization calculations, and data storage/transmission. (4) The main structure adopts a split-cabin design with a dome cabin (housing detectors) and an electronics cabin (integrating electronic devices and power systems). Through broad energy-band detection, intelligent particle discrimination, and high-speed data processing, the system achieves sub-second response times and sub-degree localization for GRBs, delivering high-precision observational data for astrophysical research.The GECAM satellite system design incorporates several key technologies: dual-satellite all-sky localization for burst sources, a main-plane sun-pointing attitude design, real-time trigger information downlink via the BeiDou-3 Global Position Reporting System, low-cost high-reliability integrated electronics, and a highly compact electromagnetic compatibility design for the satellite. These innovations ensure its cutting-edge performance in transient astrophysics observations.

GECAM is equipped with a real-time analysis system capable of rapidly processing detector data to identify and locate solar flare events [8]. This system can generate preliminary event reports within a short timeframe (typically within minutes). The data received by ground stations undergoes further processing through the scientific ground segment (BAS), which performs in-depth analysis and classification of triggered events to provide more accurate localization and categorization information [9].

The observational data from GECAM satellites will deliver crucial high-energy radiation information for solar flare research. By monitoring high-energy radiation from solar flares, GECAM is expected to reveal the acceleration mechanisms of high-energy particles, energy release processes during flares, and the relationship between flares and space weather. GECAM's dual-satellite system and all-sky field-of-view design enable nearly uninterrupted monitoring of solar flares, providing high-temporal-resolution X-ray spectra and detailed light curve structures. This capability is particularly significant for studying high-temperature/super-hot plasma and high-energy electrons.

Furthermore, GECAM's observational data will be jointly analyzed with data from other solar observation satellites (such as ASO-S/HXI and Solar Orbiter/STIX) to achieve multi-perspective stereoscopic observations of solar flares. This collaborative approach will advance the development of related theoretical models and significantly contribute to our understanding of solar flare dynamics.

3. Data

The data collected by GECAM is categorized into two types: triggered data and continuous data. When GECAM detects an outburst event (such as solar flares or gamma-ray bursts), it stores the corresponding data in triggered data files. This study utilizes GECAM observation data from its launch in 2021 to the end of 2024, during which GECAM recorded a total of 22,050 triggered events. The continuous data, on the other hand, consists of full-day data collected by GECAM. For this study, solar flare data from GECAM was primarily obtained by filtering solar flare events from the triggered data. In cases where solar flare data was incomplete, continuous data was processed to supplement the missing information. After analyzing confirmed solar flare events, we statistically examined the relationship between the right ascension and declination of solar flares and those of the Sun, establishing their positional correlation. Based on this correlation, we conducted preliminary processing of GECAM's triggered data files, identifying 2,722 candidate events that met the criteria. These events were batch-processed to generate their stacked light curves and energy-resolved light curves for further screening of potential solar flare candidates. Finally, through cross-validation with GOES satellite data, we identified 774 confirmed solar flare events. This paper will primarily focus on analyzing these 774 solar flare events.

4. Results

4.1 Localization of Solar Flares

This study first identified 100 confirmed solar flare events by referencing GOES satellite data. Using the information of these flares, we located their corresponding triggered data files in GECAM's triggered data list. From these files, we extracted the right ascension (RA) and declination (Dec) of the solar flares, as well as the RA and Dec of the Sun's center point at the time of the flare occurrence.

After calculating the absolute differences between these coordinates, we determined the positional relationship of the solar flares relative to the Sun. The scatter plot (shown in Figure 2) illustrates this positional relationship. In the plot, the two dashed lines represent an absolute difference of 20° in RA and Dec, respectively. The horizontal axis indicates the absolute difference in RA, while the vertical axis indicates the absolute difference in Dec.

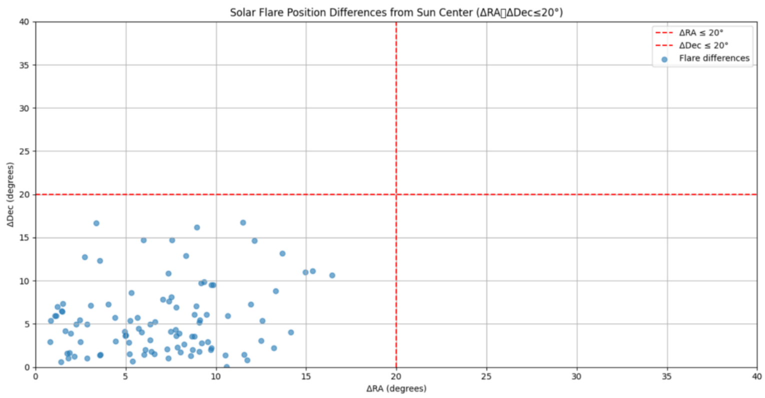


Figure 2: Scatter plot of absolute differences in right ascension and declination between solar flares and the Sun's center point

This analysis provides a clear visualization of the spatial distribution of solar flares in relation to the Sun's center.

4.2 Localization of Solar Flares

Based on the screened solar flare data, we classified these flares according to their intensity levels (as shown in Figure 3). The analysis reveals that among solar flares observed from 2021 to 2024, C-class flares accounted for the highest proportion at approximately 59.2%, while X-class flares were the least frequent, constituting only about 2.5%. The relatively small number of B-class flares (approximately 9.8%) may be attributed to GECAM's higher energy detection range, which makes it less sensitive to detecting weaker B-class flares. In terms of temporal distribution, the year 2021 recorded the fewest flare events, with a gradual increase observed in subsequent years. This pattern suggests that 2021 likely marked the ascending phase of the current solar activity cycle.

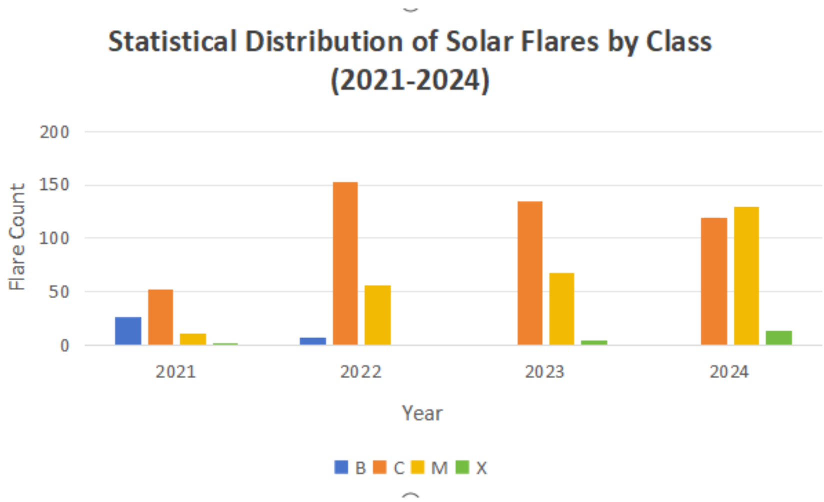
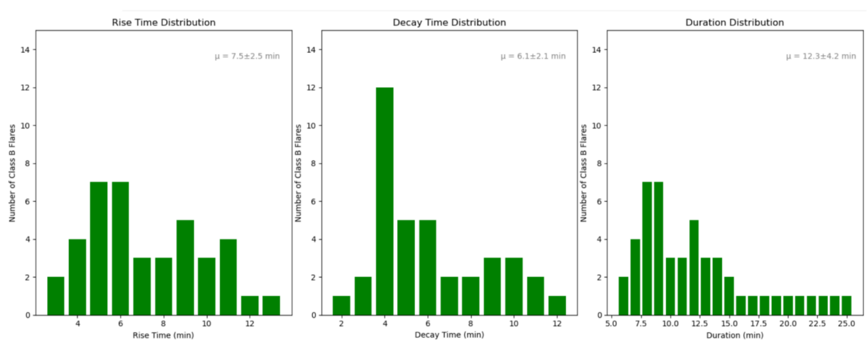


Figure 3: Statistical Chart of Solar Flare Counts by Class (2021-2024)

4.3 Statistics of flare parameters including rise time, decay time, and duration

This paper presents statistics on the rise time, decay time, and duration of solar flares of different classes (B, C, M, and X) from 2021 to 2024 (as shown in Figure 4). The figure displays the relationship between the rise time, decay time, and duration of B, C, M, and X-class flares and their corresponding counts. The bottom row shows the temporal distribution of the overall sample, where μ represents the population mean for each plot. The general characteristics of these plots can be observed.

For all flare classes, the rise time is longer than the decay time, leading us to conclude that the longer duration of solar flares in recent years is primarily due to their extended rise time. The duration of flares also increases with their intensity class. Due to the limited number of M-class flares, only their duration is plotted. The longest duration was recorded for an M3.4-class flare, lasting 134 minutes, while the shortest duration was observed for an X1.1-class flare, persisting only about 5 minutes.



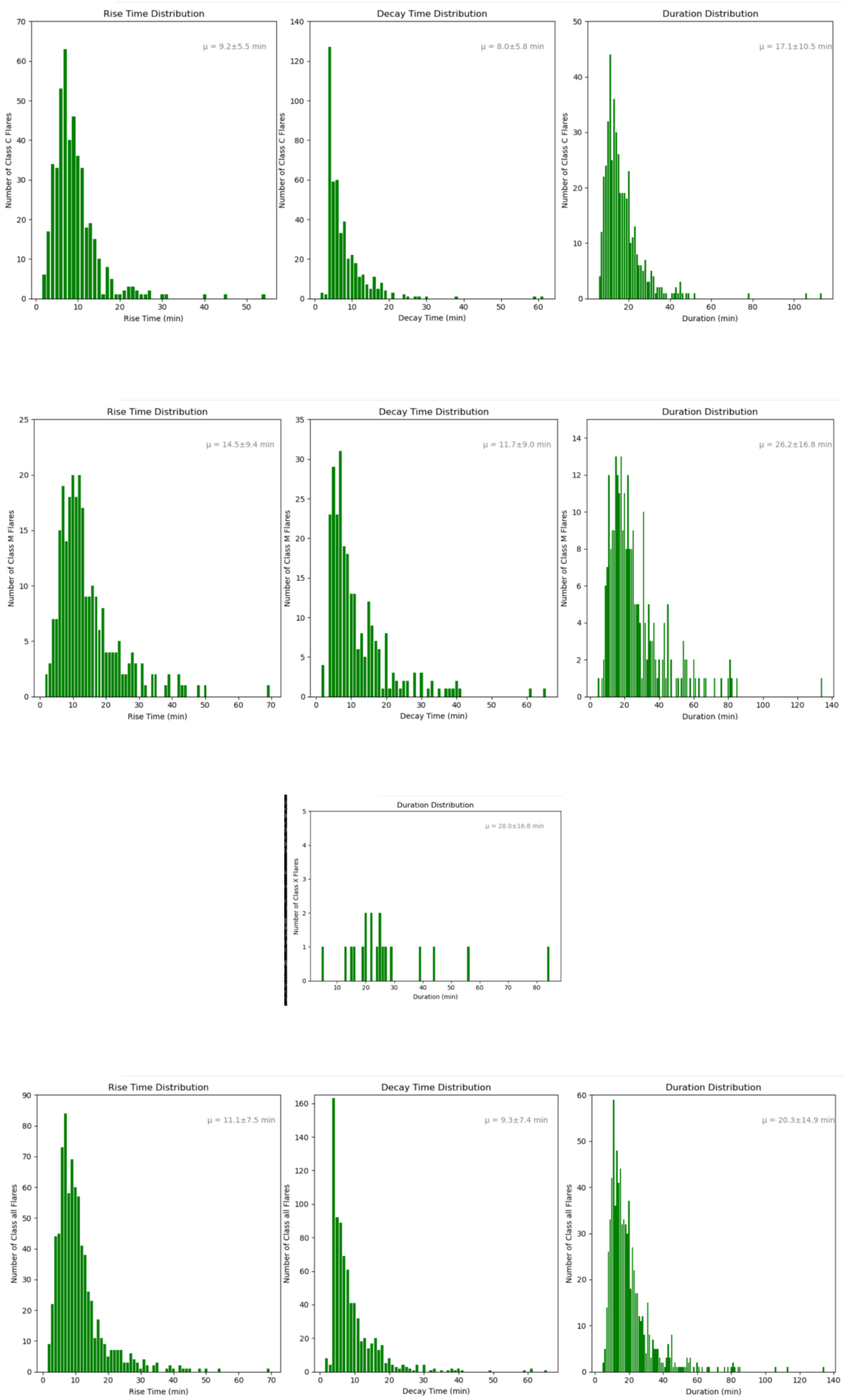


Figure 4: Comparison of rise time, decay time, and duration across different flare classes

5. Summary

With its high temporal resolution and full-sky coverage capabilities, GECAM has significantly advanced solar flare research. This study establishes a comprehensive catalog of 774 solar flare events observed by GECAM between 2021 and 2024, systematically analyzing their spatiotemporal characteristics and energy release processes. Key findings include: C-class flares dominate the sample while X-class flares are least frequent - a distribution pattern closely tied to GECAM's high-energy detection band configuration. The flare durations are primarily determined by their rising phases and show marked increases with flare intensity grades. Through cross-validation of GECAM's high-energy radiation data with multi-source observations including GOES satellites, this work reveals both commonalities and differences in energy release processes across flare classes. These results provide crucial observational evidence for understanding solar eruption mechanisms and their space weather impacts, highlighting GECAM's pivotal role in multi-messenger astronomy and solar physics research.

6. Acknowledgments

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