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Progress of GECAM Observation Research

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Abstract Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (GECAM) is a constellation with four instruments (launch date): GECAM-A/B (10 December 2020), GECAM-C (27 July 2022) and GECAM-D (13 March 2024), which are dedicated to monitoring gamma-ray transients in all-sky. The primary science objectives of GECAM include Gamma-Ray Bursts (GRBs), Soft Gamma-ray Repeaters (SGRs), high energy counterparts of Gravitation Wave (GW) and Fast Radio Burst (FRB), Solar Flares (SFLs), as well as Terrestrial Gamma-ray Flashes (TGFs) and Terrestrial Electron Beams (TEBs). A series of observations and research have been made since the launch of GECAM-A/B. GECAM observations provide new insights into these high-energy transients, demonstrating the unique role of GECAM in the "multi-wavelength, multi-messenger" era.

Key words GECAM, Gravitational wave electromagnetic counterpart, High energy transients

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1 Introduction

Gamma-ray transients are phenomena with a sudden increase in gamma-ray flux from celestial objects in the distant universe. Since the first observation of a Gamma-Ray Burst (GRB) in 1967, various gamma-ray transient sources have been discovered. Especially in recent years, the operation of advanced gamma-ray instruments has enabled rapid progress in the study of gamma-ray transients and related phenomena. A milestone event is the observation of the Gravitational Wave (GW) produced by the merger of binary neutron stars (GW170817) and the GW-associated Gamma-Ray Burst (GWGRB), GRB 170817A, heralding a new era in "multi-messenger, multi-wavelength" time-domain astronomy[1]*. The pursuit of the GWGRB is the primary motivation of GECAM mission.

GECAM is originally a constellation of two small X-ray and gamma-ray all-sky space telescopes funded and built by the Chinese Academy of Sciences. These two microsatellites, denoted as GECAM-A and GECAM-B, were launched on 10 December 2022 (Bei-

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* https://gcn.nasa.gov/circulars/21520

jing Time). SATech-01/HEBS is the 3rd GECAM monitor which was on board the SATech-01 satellite launched on 27 July 2022, thus it was called GECAM-C. DRO/GTM is the 4 th instrument in GECAM series which was launched on 13 March 2024 on board the DRO-A satellite thus also named as GECAM-D. Currently, GECAM has established the capability of monitoring the full sky all the time in a wide energy range (*i.e.* 6 keV to 5 MeV).

The primary science objectives of GECAM are various types of gamma-ray transients, including GW-GRBs, GRBs, SGRs and high-energy counterparts of Fast Radio Bursts (FRBs). Moreover, SFLs, TGFs and TEBs are also important targets of GECAM.

GECAM data and analysis software have been released*.

2 GRB

GRB is the most violent stellar explosive phenomenon in the universe which can last from a few milliseconds to hours. Long GRBs, whose duration is usually over 2 seconds, originate from the collapse of massive stars, while short GRBs, often less than 2 seconds, are believed to result from the merger of binary neutron stars or a neutron star and a black hole. GRBs from the compact merger are likely associated with GW signal.

2.1 BOAT—GRB 221009A

GRB 221009A, as the brightest gamma-ray Burst Of All Time (BOAT), was detected by many instruments in multi-wavelength. Most space gamma-ray telescopes suffered severe data saturation and instrumental effects during the main emission of GRB 221009 A. Remarkably, GECAM-C provided the best measurement of this burst with accurate and high-resolution data with negligible instrumental effects**.

Based on the joint analysis of GECAM-C and *Insight*-HXMT, a comprehensive and precise measurement of the BOAT GRB was achieved, including precursor, main burst, flare and early afterglow, as shown in Figure 1(a). Especially GECAM-C provided the most precise observations of the extremely bright main burst[4]. The observations of GECAM-C and *Insight*-HXMT revealed that GRB 221009A has a record-breaking isotropic equivalent energy $E_{\rm iso}$ up to 10^{55} erg (1 erg= 10^{-7} J). In addition, a break in the flux light curve of the early afterglow was also identified to be a jet break. Based on the time of this jet break, $E_{\rm iso}$, and redshift of this GRB, the jet opening angle of the GRB 221009A was estimated to be only about 0.73 degrees[2].

Zheng *et al.* [3] conducted a detailed joint analysis of the early afterglow of GRB 221009A from 660 to 1860 seconds after the trigger with the data from *Insight*-HXMT, GECAM-C, and Fermi/GBM. They found that the early afterglow spectrum of GRB 221009A has two components — a cutoff power-law with an additional power-law, generally forming a V shape, which is depicted in Figure 1(b). Additionally, by fitting the flux light curves in different energy bands, the break time is well consistent from keV to TeV, *i.e.* achromatic break feature, further confirming that it is a jet break. Interestingly, the analysis indicates that the slopes of the flux

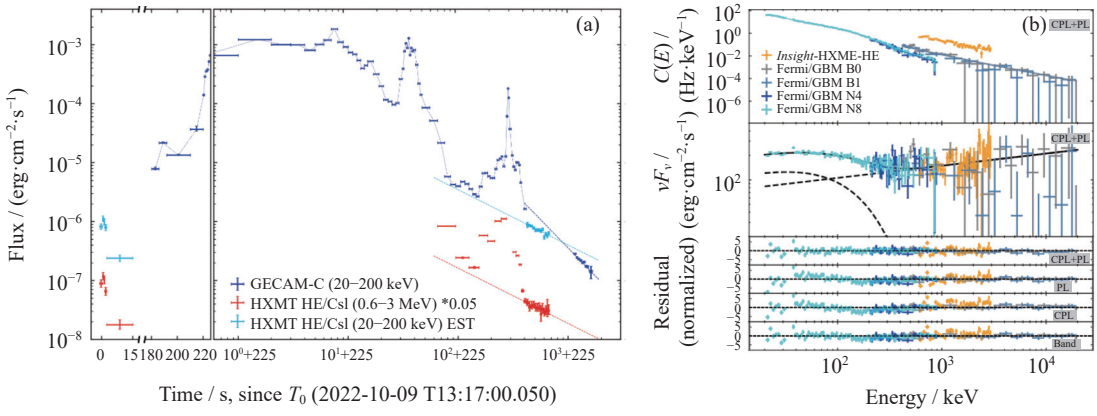

Fig. 1 (a) Light curves of GRB 221009A[2]. (b) Spectra of the early after glow of GRB 221009A [3]

* http://gecam.ihep.ac.cn/grbDataAnalysisSoftware.jhtml
** https://gcn.nasa.gov/circulars/32751

light curves before and after the break vary with energy, and tend to be consistent as the energy decreases. These observational results provide strong evidence that the jet of GRB 221009A is structured with an extremely narrow and bright core.

By taking the advantage of the unsaturated data of GECAM-C, Zhang *et al*. [4] performed a comprehensive spectral analysis and line search of GRB 221009A jointly with GECAM-C and Fermi/GBM data and found profound spectral excess features in multiple time intervals. After comprehensive analyses especially on the sophisticated background modeling, instrument effects investigation and cross-check between two instruments, they firmly identified the spectral excess as emission line with central energy up to about 37 MeV during the bright part of this burst where other instrument except for GECAM-C cannot explore. Remarkably, they discovered that the central energy and the energy flux of emission lines follow a power-law decay with time, with power-law indices of −1 and −2, respectively, providing unambiguous evidence of the reality and GRB origin of these emission lines. On the other hand, they found that the ratio of the line width to the line central energy seems not to evolve as time. According to their unique findings, they suggested that the observed emission line cannot be explained by the high latitude effect of a uniform top-hat jet, instead they could be explained as the blue-shifted of electron positron pair annihilation 511 keV line in the jet, thus the bulk Lorentz factor of the jet could be measured directly from the emission line for the first time during the prompt emission. They also reported a low significant absorption line feature in the GECAM data in this GRB. These discoveries of the spectral line features provide new insights into the physics of GRB and relativistic jets.

To investigate the time-resolved spectra of GRB 221009A, Yang *et al*. [5] fit the GECAM-C and Fermi/GBM data with a synchrotron radiation model, assuming an expanding emission region with relativistic speed and a global magnetic field decaying with radius. Their results indicate that the spectra of this burst are consistent with a synchrotron origin from relativistic electrons accelerated at a large emission radius. The lack of thermal emission in the prompt emission spectra supports a Poynting flux-dominated jet composition.

2.2 The Second Brightest GRB — GRB 230307A

GRB 230307A is another important GRB, not only because it has the second-highest brightness[6], but also because it is a long-duration burst with merger origin. As an atypical long-short burst, GRB 230307A, along with GRB 211211A, represents a new type of type I GRB which could be associated with a GW event. The extremely high brightness also caused data saturation in other instruments (*e.g.* Fermi/GBM). However, thanks to the dedicated design, both GECAM-B and GECAM-C accurately and completely recorded this profound burst without data problems, resulting in a series of important and interesting discoveries.

Sun *et al*. [6] conducted a comprehensive analysis of the broad-band prompt emission of GRB 230307A based on the data from GECAM and LEIA. They show that, despite of its apparently long duration, the properties of prompt emission and host galaxy suggest that this GRB has a compact star merger origin, which is consistent with its association with a kilonova. Another interesting phenomenon was discovered in this peculiar GRB: as the gamma-ray radiation disappears, an extended X-ray radiation component detected by LEIA appears, indicating the emergence of a magnetar central engine. Additionally, an achromatic temporal break in the hard X-ray light curves of GECAM during the prompt emission phase is identified, which is considered as an edge effect of the jet. This is the first time that such an effect is seen in the prompt emission phase and could be used to constrain the geometry of the jet.

In another study of this burst, Yi *et al*.[7] noticed that the complex multi-peak (*i.e.* narrow pulse) structure in the light curve of GRB 230307A can be well-fitted by a Fast Rise Exponential Decay (FRED) function, and the spectrum shows a regular time evolution. By fitting the light curves in different energy bands with FRED function, a clear spectral lag of the full FRED shape is found, while the spectral lag of the narrow pulses is negligible. Additionally, it was also discovered that the overall light curve exhibits self-similarity feature. The authors find that these behaviors are difficult to be explained by the internal shock model, lending strong support to the ICMART model.

3 SGR

SGRs are repeated, intense bursts in the X-ray and soft gamma-ray bands from a special type of neutron stars with extremely strong magnetic fields (*i.e.* magnetar).

Among those SGRs monitored by GECAM, SGR J1935+2154 is peculiar and well-known for its prolific bursts (also called X-Ray Burst, XRB) and for the first identification as the source of an FRB (*i.e.* FRB 200428). Importantly, GECAM also detected an XRB on 14 October 2022 from SGR J1935+2154 which is associated with a radio burst*, confirming the association between XRB and FRB.

Xie *et al.* [8] collected an updated burst sample from SGR J1935+2154, including all bursts reported by Fermi/GBM and GECAM till 2022 January and the targeted-search bursts in the Fermi/GBM data from August 2008 to December 2014 . They found that the bursts of SGR J1935+2154 exhibit a periodicity of about 126 days. Moreover, they suggest that this periodicity may be interpreted as the precession of the magnetar.

By using the Li-CCF, a novel cross-correlation function method, Xiao *et al.* [9] conducted a spectral lag analysis of the burst sample from SGR J1935+2154 detected by several instruments including GECAM (some events are shown in the Figure 2), and found that there is a linear relationship between the time lag and photon energy (the higher-energy photons arrive earlier). They also found that the distribution of the slopes of the linear relationship can be fitted with three Gaussians. This research shows that spectral lag analysis could serve as an important tool for investigating the radiation mechanism of SGRs.

The Minimum Variation Timescale (MVT) is an important probe for the physical mechanisms of SGR. Xiao *et al.* [10] noticed that the peak of the MVT of SGR J1935+2154 is about 2 ms, based on data from GECAM, Fermi/GBM and *Insight*-HXMT. This time scale corresponds to the emission region of about 600 km, which is comparable to the scale of the magnetosphere of a pulsar, lending supports to the magnetosphere origin of the magnetar burst. The authors also found that, just like spectral lag, the energy dependence of MVT of SGR is also different from that of GRB. These findings are very helpful to distinguish whether a burst originates from a magnetar or GRB.

Quasi-Periodic Oscillations (QPOs) have been reported in some magnetars. Xiao *et al.* [11] employed a Power Density Spectrum (PDS) method to search for the QPOs in hundreds of XRBs from SGR J1935+2154 observed by GECAM, *Insight*-HXMT and Fermi/GBM from July 2014 to January 2022 . Although no definitive QPO signal (significance >3σ) was detected in individual bursts or in the averaged periodogram of bursts grouped by duration, several bursts were identified as exhibiting features at about 40 Hz, which could be explained as the proximity intervals between adjacent pulses of XRB. This study also found that the distribution of the slopes of the PDS of this XRB sample peaks at about 2.5, which is consistent with other magnetars but higher than the commonly observed 5/3 in GRBs.

In another study, Xiao *et al.* [12] combined the above research results and found that the differential and cumulative distributions of MVT and spectral lag of SGR J1935+2154 follow the power-law model and the fluctua-

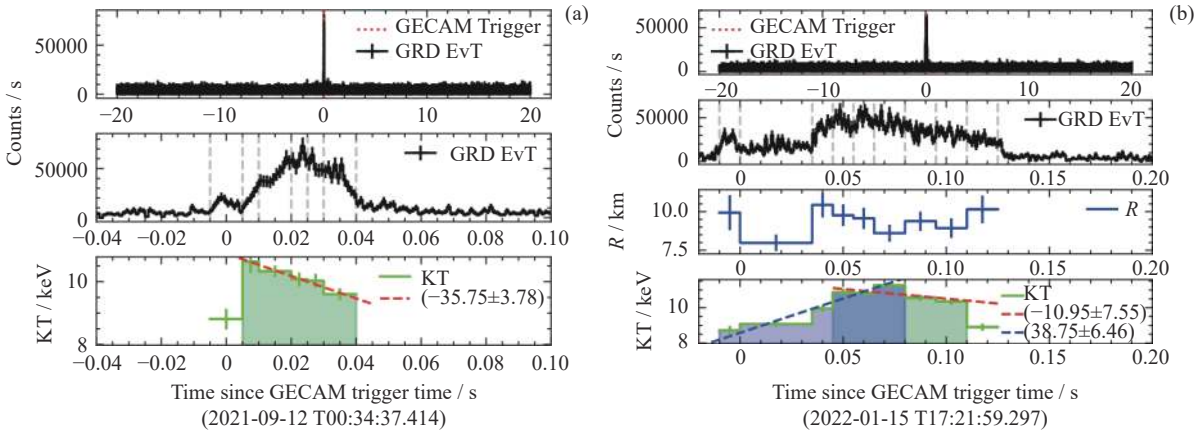

Fig. 2 Light curves and the evolution of the Blackbody Temperature (KT) with time of two bursts from SGR J1935+2154[9]: trigger time of burst is 2021-09-12T00:34:37.414 for panel (a) and 2022-01-15T17:21:59.297 for panel (b)

* https://www.astronomerstelegram.org/?read=15682

tions in both parameters follow the Tsallis q-Gaussian distributions, with consistent q value across different scale intervals. These results suggest that both the MVT and spectral lag are scale-invariant, providing new parameters for studying the Self-Organized Criticality (SOC) systems.

4 SFL and TGF

Thanks to its large field of view, GECAM can provide a nearly continuous monitoring of the Sun in hard X-ray and soft gamma-ray band. Besides, the usage of Charged Particle Detectors (CPD) makes GECAM having the ability to distinguish charged particles and high-energy photons, which is vital to observing the TGFs and TEBs from the Earth.

4.1 SFL

As a X-ray monitor for the Sun, GECAM features a very high temporal resolution (0.1 microseconds) and wide energy band (about 6 keV to 5 MeV). In addition, GECAM itself has the capability of localization to determine whether a burst comes from the Sun.

By investigating the high-time resolution data from GECAM of the M9.6 solar flare event on 21 April 2022 at 01:52 UTC, Zhao *et al.*[13] discovered significant paired QPPs with a short period in the precursor phase in hard X-ray band, which is very rare in the precursor phase. And the QPPs are confirmed by the joint analysis of the microwave data obtained by NoRP and RSTN. Combining the image data of the Sun, the authors found that the observed properties of paired QPP are in good agreement with the scenario of the current loop coalescence model.

4.2 TGF

To measure and distinguish the TGFs and TEBs, dedicated designs have been implemented to GECAM, including the usage of both the Gamma-Ray Detector (GRD) and Charged Particle Detector (CPD) with high temporal resolution and short dead time.

Zhao *et al.*[14] conducted a systematic search in the GECAM-B data from December 2020 to September 2022, and found 147 bright TGFs, 2 typical TEB events, and 2 special TEB-like events, corresponding to a discovery rate of about 200 TGFs per year for GECAM-B. The geographical distribution of these events is depicted in Figure 3. The statistical properties such as the lightning-association ratio, duration, and hardness ratio of GECAM TGFs were systematically investigated. They found that there are some unique and interesting events, such as the double-peaked TGFs characterized by two about 100 μs pulses with very similar temporal and spectral structures, and the quadruple-peaked TEB-like events, which pose challenges in the understanding of such phenomena.

5 Summary

To monitor the gamma-ray transients especially the GW-GRBs, GECAM was proposed and originally designed to be composed of two microsatellites *i.e.* GECAM-A and GECAM-B, in the same Low Earth Orbit but with opposite orbital phase to cover the full sky. Since the launch of these two GECAM microsatellites on 10 December 2020, now GECAM has grown to be a constellation of four instruments on different spacecrafts. Thanks to the dedicated design in the detector and electronics, GECAM played a unique role in measuring the bright bursts with very high time resolution in a wide energy band. Indeed, GECAM has successfully and accurately measured the two brightest ever GRBs (GRB 221009A and GRB 230307A) without data saturation and other instrumental effects, resulting in fruitful achievements in understanding these two amazing events and GRB physics. Importantly, GECAM detected many SGR

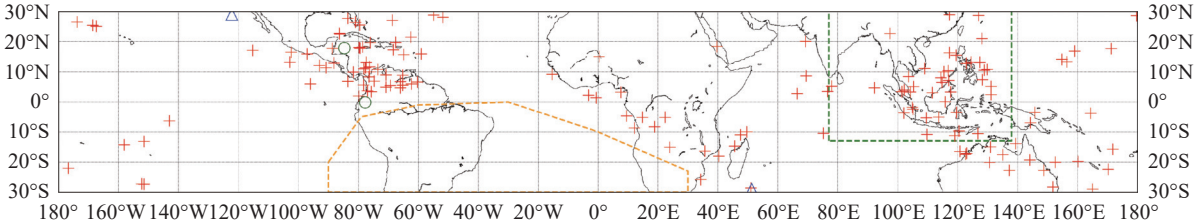

Fig. 3 Geographical distribution of GECAM TGFs, including 147 TGFs (red pluses), 2 TEBs (green circles) and 2 TEB-like events (blue triangles). The green dashed lines show the east Asia region while the orange dashed lines represent the South Atlantic Anomaly (SAA)[14]

bursts including those associated with radio bursts from SGR J1935+2154, decisively confirming the association between SGR X-ray burst and fast radio burst. GECAM also made great contributions to the observation and study of SFL, TGF and TEB, especially discovered a new type of high energy phenomenon tentatively called TEB-like event. Looking into the future, GECAM is expected to continue to play an important role in the "multi-wavelength, multi-messenger" astronomy as well as the high energy emission from the Sun to the Earth.

References

[1] ABBOTT B P, ABBOTT R, ABBOTT T D, *et al*. Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A[J]. *The Astrophysical Journal Letters*, 2017, **848**(2): L13

[2] AN Z H, ANTIER S, BI X Z, *et al*. Insight-HXMT and GECAM-C observations of the brightest-of-all-time GRB 221009A [OL]. arXiv preprint arXiv: 2303.01203, 2023. DOI:10.48550/arXiv.2303.01203

[3] ZHENG C, ZHANG Y Q, XIONG S L, *et al*. Observation of GRB 221009A early afterglow in X-Ray/gamma-ray energy bands[J]. *The Astrophysical Journal Letters*, 2024, **962**(1): L2

[4] ZHANG Y Q, XIONG S L, MAO J R, *et al*. Observation of spectral lines in the exceptional GRB 221009A[J]. *Science China Physics, Mechanics & Astronomy*, 2024, **67**(8): 289511

[5] YANG J, ZHAO X H, YAN Z Y, *et al*. Synchrotron radiation dominates the extremely bright GRB 221009A[J]. *The Astrophysical Journal Letters*, 2023, **947**(1): L11

[6] SUN H, WANG C W, YANG J, *et al*. Magnetar emergence in a peculiar gamma-ray burst from a compact star merger[OL]. arXiv preprint arXiv: 2307.05689, 2023. DOI: 10.48550/arXiv.2307.05689

[7] YI S X, WANG C W, SHAO X Y, *et al*. Evidence of mini-jet emission in a large emission zone from a magnetically-dominated gamma-ray burst jet[OL]. arXiv preprint arXiv: 2310.07205, 2023. DOI: 10.48550/arXiv.2310.07205

[8] XIE S L, CAI C, XIONG S L, *et al*. Revisit the periodicity of SGR J1935+2154 bursts with updated sample[J]. *Monthly Notices of the Royal Astronomical Society*, 2022, **517**(3): 3854-3863

[9] XIAO S, TUO Y L, ZHANG S N, *et al*. Discovery of the linear energy dependence of the spectral lag of X-ray bursts from SGR J1935+2154[J]. *Monthly Notices of the Royal Astronomical Society*, 2023, **521**(4): 5308-5333

[10] XIAO S, YANG J J, LUO X H, *et al*. The minimum variation timescales of X-ray bursts from SGR J1935+2154[J]. *The Astrophysical Journal Supplement Series*, 2023, **268**(1): 5

[11] XIAO S, LI X B, XUE W C, *et al*. Individual and averaged power density spectra of X-ray bursts from SGR J1935+2154: quasi-periodic oscillation search and slopes[J]. *Monthly Notices of the Royal Astronomical Society*, 2024, **527**(4): 11915-11924

[12] XIAO S, ZHANG S N, XIONG S L, *et al*. The self-organized criticality behaviours of two new parameters in SGR J1935+2154[J]. *Monthly Notices of the Royal Astronomical Society*, 2024, **528**(2): 1388-1392

[13] ZHAO H S, LI D, XIONG S L, *et al*. Paired quasi-periodic pulsations of hard X-ray emission in a solar flare[J]. *Science China Physics, Mechanics & Astronomy*, 2023, **66**(5): 259611

[14] ZHAO Y, LIU J C, XIONG S L, *et al*. The first GECAM observation results on terrestrial gamma-ray flashes and terrestrial electron beams[J]. *Geophysical Research Letters*, 2023, **50**(14): e2022GL102325

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