GRB 230911A: The First Discovery of a Fermi GRB Optical Counterpart with the Gravitational-wave Optical Transient Observer (GOTO)

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Abstract

We report on the detection of candidate optical counterpart GOTO23akf/AT2023shv to the GRB 230911A with the Gravitational-wave Optical Transient Observer (GOTO) instruments located at La Palma, Canary Islands, and Siding Spring Observatory, Australia. The Fermi Gamma-ray Burst Monitor, which finds gamma-ray bursts (GRBs) nearly every two days, detected GRB 230911A with a statistical uncertainty of $4\overset{\circ}{.}1$. However, the large (~10–100 deg^2) localization areas mostly impede the rapid identification of an optical counterpart. GOTO facilities fully covered 90% localization area of the GRB 230911A. We proposed GOTO23akf as the optical afterglow of GRB 230911A, subsequently confirmed through Swift-X-Ray Telescope observations in which an uncatalogued X-ray source spatially coincident with the GOTO candidate was detected. This is the first optical afterglow discovery for a Fermi GRB with the newly expanded GOTO network.

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1. Introduction

Observing the prompt emission and early afterglow phases of cosmic gamma-ray bursts (GRBs) in the optical range is challenging due to the necessity for precise burst localization by spacecraft and the relatively slow response of ground-based optical instruments to reports of their detection. Presently, GRBs identification predominantly relies on observations facilitated by the Swift and Fermi satellites. Swift's X-Ray Telescope (XRT; Burrows et al. 2005) and Ultra-Violet and Optical Telescope (Roming et al. 2005) search for electromagnetic counterparts corresponding to triggers detected by the Swift Burst Alert Telescope (Barthelmy et al. 2005). Although the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) exhibits larger localization uncertainties than Swift, it significantly contributes to the GRB detection rate, identifying approximately one event per two days. As there is no X-ray or optical instrument on board Fermi, if Swift does not jointly detect the GRBs, the localization areas become too large (tens of square degrees) for targeted observations. In such cases, telescopes with large fields of view (FoV) that can automatically respond to receiving an alert and conduct observations play a key role.

The Gravitational-wave Optical Transient Observer (GOTO; Steeghs et al. 2022) comprises a network of wide-field optical telescopes GOTO-North, located in Roque de los Muchachos Observatory (La Palma, Spain) and GOTO-South in Siding Spring Observatory (Australia), for the systematic monitoring of the variable optical sky. Its primary goal is to search for optical counterparts to gravitational wave (GW) sources (e.g., Gompertz et al. 2020), achieving moderate depth ($L \approx 20$ mag) over a wide FoV to accommodate the typically large (∼100s of square degrees) LIGO/Virgo uncertainty regions. The combined FoV of each telescope is ∼40 square degrees, with two instruments at each site. The antipodal positioning of the instruments allows for quasi-continuous sky monitoring, enabling observations of sources in both hemispheres.

(e.g., Dyer et al. 2020) GOTO operates in two modes: trigger and sky-survey. In trigger mode, it promptly responds to a transient detection alert, prioritizing observations of the source localization area over other observation programs. Sky-survey coverage with a 2–3 days cadence updates templates for the subtraction procedure necessary for identifying candidates for the source. GOTO's wide FoV facilitates fast execution of both modes, making it suitable for covering not only LIGO/Virgo/KAGRA but also Fermi localizations that can exceed ten square degrees.

We present the results of Fermi GRB 230911A observations by GOTO. We discuss the data processing, source identification, and its subsequent confirmation, marking the first-ever afterglow discovery of a Fermi GRB during GOTO's operational history.

2. Observations

GRB 230911A was registered by Fermi-GBM at 2023 September 11 UT 03:09:32 (trigger 716094577.87568/230911132, Fermi GBM Team 2023). In a subsequent gamma-ray pulse analysis, it was discovered the burst had a duration of $T_{90} \approx 36$ s, indicating it to be likely a long GRB (Roberts et al. 2023).

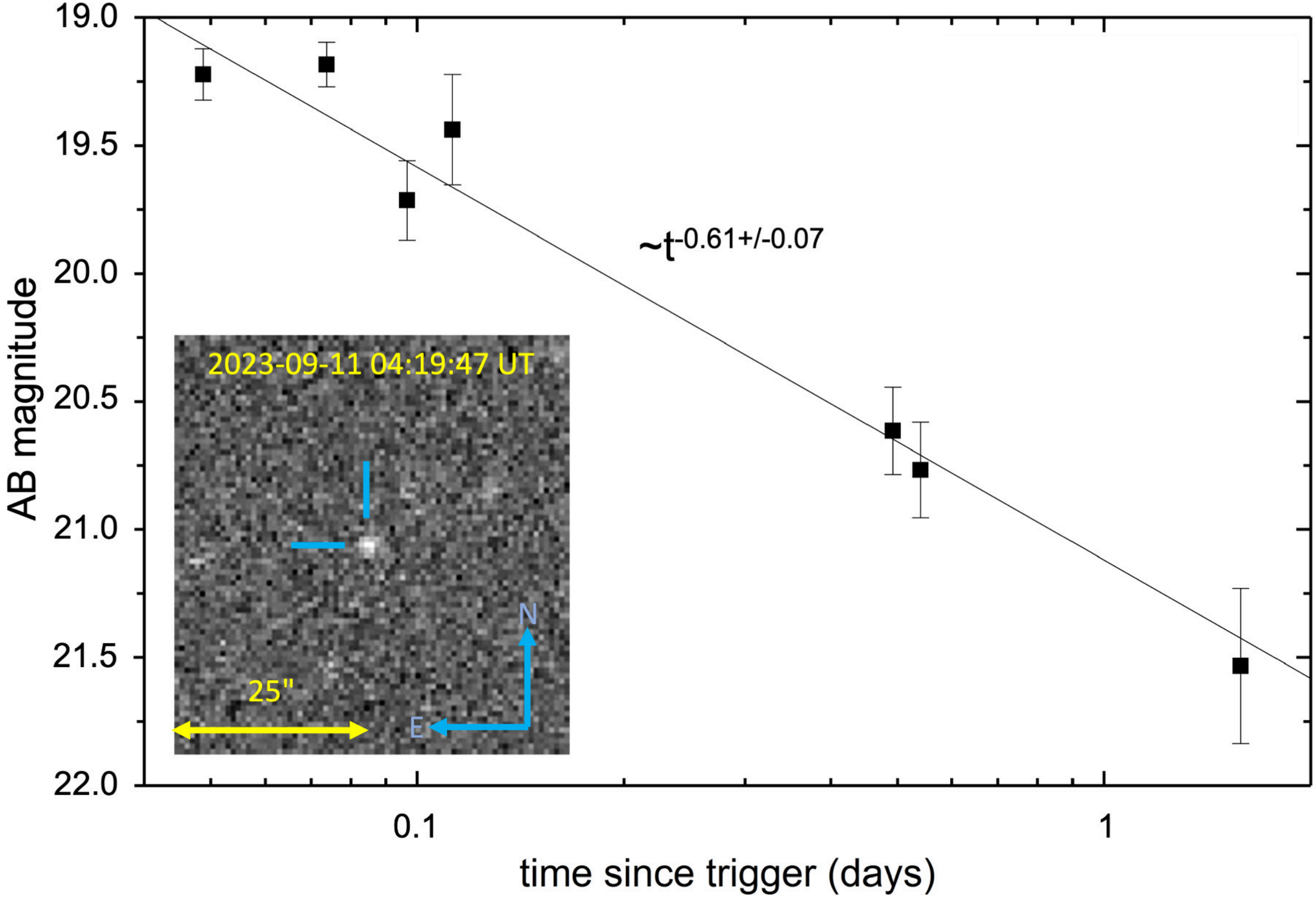
GOTO's trigger observations started at 04:19:47 UT on 2023 September 11 and consisted of 7 sets of 4 × 90 s exposures in the GOTO *L*-band (400–700 nm) from 1.17 to 37.98 hr post trigger using both GOTO-North and GOTO-South facilities.

Images were processed immediately after acquisition using the GOTO pipeline (Lyman et al. 2024, in preparation). The standard survey approach for GOTO includes four exposures per pointing, subjected to standard CCD reduction. Exposure sets are then combined using a weighted-mean approach. The resulting combined images are then aligned (Lyman 2021) and matched to a reference template of the same pointing. A multi-threaded version of the HOTPANTS algorithm (Becker 2015) is used to produce a difference image. SEP (Barbary 2016), based on the algorithm of SExtractor (Bertin & Arnouts 1996), is used for source extraction to identify residual sources in the difference image. Detections in the difference image that met a specified cut on the real-bogus score of the GOTO "real-bogus" classifier (Killestein et al. 2021) are sent to GOTO collaborators for source vetting and follow-up investigation of candidates. In the case of GOTO23akf, the "real-bogus" classifier operated accurately, rejecting all other candidates and retaining only one, which was later confirmed to be associated with GRB 230911A.

3. Results

We identified one candidate optical counterpart within the GBM 90% localization region, GOTO23akf R.A.(J2000) = $03{:}50{:}00\overset{\prime\prime}{.}51 \pm 0\overset{\prime\prime}{.}3$, decl. (J2000) = $-29{:}49{:}30\overset{\prime\prime}{.}66 \pm 0\overset{\prime\prime}{.}3$. We found no evidence of this source before the GRB trigger time in previous GOTO observations, Zwicky Transient Facility observations provided by the Lasair broker (Smith et al. 2019), or the ATLAS forced photometry server (Shingles et al. 2021). We reported the candidate to the Transient Name Server[23] and designated as AT 2023shv (Belkin et al. 2023).

Figure 1 displays photometry results, showing a power-law decay with a temporal index of -0.61 ± 0.07. When extrapolated to the next night (2023 September 13), predictions yielded a $L \sim 21.9$ mag, significantly fainter than the characteristic 5σ upper limit of the images. Consequently, further observations were discontinued.



AB magnitude
19.0
19.5
20.0
20.5
21.0
21.5
22.0
0.1
1
time since trigger (days)
~t$^{-0.61+/-0.07}$
2023-09-11 04:19:47 UT
25"
N
E

Figure 1. GOTO *L*-band light curve of GRB 230911A with a single power-law (SPL) model fit. Inset: GOTO-North image of the GRB 230911A first detection.

After the discovery of the possible candidate, we applied for the Swift-XRT Target of Opportunity observations, which were performed between ~2.49 and ~3.78 days after the trigger. They revealed an uncatalogued X-ray source consistent with our GOTO candidate (D'Avanzo et al. 2023).

Nowadays, GOTO covers over 80% of the localization areas for around 50% of Fermi GRBs. The discovery of a Fermi GRB 230911A optical counterpart demonstrates GOTO's ability to rapidly survey extensive sky areas for new transients. This provides a high level of confidence that optical counterparts to GW events will be accessible to GOTO during future operations of LIGO/Virgo/KAGRA.

Acknowledgments

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Footnotes

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[23] https://www.wis-tns.org

[24] https://goto-observatory.org