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GRB 221009A: Discovery of an Exceptionally Rare Nearby and Energetic Gamma-Ray Burst

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Abstract

We report the discovery of the unusually bright long-duration gamma-ray burst (GRB), GRB 221009A, as observed by the Neil Gehrels Swift Observatory (Swift), Monitor of All-sky X-ray Image, and Neutron Star Interior Composition Explorer Mission. This energetic GRB was located relatively nearby ($z = 0.151$), allowing for sustained observations of the afterglow. The large X-ray luminosity and low Galactic latitude ($b = 4.^\circ 3$) make GRB 221009A a powerful probe of dust in the Milky Way. Using echo tomography, we map the line-of-sight dust distribution and find evidence for significant column densities at large distances ($\gtrsim$10 kpc). We present analysis of the light curves and spectra at X-ray and UV–optical wavelengths, and find that the X-ray afterglow of GRB 221009A is more than an order of magnitude brighter at $T_0 + 4.5$ ks than that from any previous GRB observed by Swift. In its rest frame, GRB 221009A is at the high end of the afterglow luminosity distribution, but not uniquely so. In a simulation of randomly generated bursts, only 1 in 10^4 long GRBs were as energetic as GRB 221009A; such a large $E_{\gamma,\mathrm{iso}}$ implies a narrow jet structure, but the afterglow light curve is inconsistent with simple top-hat jet models. Using the sample of Swift GRBs with redshifts, we estimate that GRBs as energetic and nearby as GRB 221009A occur at a rate of $\lesssim$1 per 1000 yr—making this a truly remarkable opportunity unlikely to be repeated in our lifetime.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629)

1. Introduction

Massive stars exhibit a broad continuum of properties in their terminal explosions. At one end are the cosmological long-duration gamma-ray bursts (GRBs), capable of coupling tremendous energies ($\gtrsim 10^{51}$ erg) to highly collimated ejecta with a bulk Lorentz factor $\Gamma_0 \gtrsim 100$ (Piran 2004). On the other end, the energy budget of most stripped-envelope core-collapse supernovae is dominated by the (quasi)-isotropic supernova emission, with photospheric velocities of tens of thousands of kilometers per second (e.g., Liu et al. 2016). Intermediate between these two extremes lies the growing class of low-luminosity GRBs and relativistic supernovae (e.g., Margutti et al. 2014). Typified by the prototypical low-luminosity GRB 980425 associated with SN 1998bw (Galama et al. 1998; Kulkarni et al. 1998), these sources couple several orders of magnitude less energy to their moderately relativistic ejecta ($\sim 10^{48}$ erg), and lack the high degree of collimation of cosmological GRBs.

In the nearby universe ($z \lesssim 0.3$), where high-energy facilities are sensitive to low-luminosity GRBs, high-luminosity GRBs are exceedingly rare due to their much lower volumetric rate. Yet an energetic GRB observed within this volume could produce unprecedented brightness. Here we report the discovery of GRB 221009A, an extremely luminous GRB (Kann & Agui Fernandez 2022) in our cosmic backyard.

On 2022 October 9 at 14:10:17 UT, the Burst Alert Telescope (BAT; Barthelmy et al. 2005), on board the Neil Gehrels Swift Observatory (Swift; Gehrels et al. 2004), triggered twice in rapid succession on a new cosmic source in the constellation Sagitta. Following its automated burst response, Swift promptly slewed to the location of the first trigger, detecting a bright transient seen with both the Swift X-Ray Telescope (XRT; Burrows et al. 2005) and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005). Due to the rarity of such a repeated BAT image trigger and the proximity of the source to the Galactic plane ($b = 4\overset{\circ}{.}3$), it was initially classified as a new Galactic X-ray and optical transient, and therefore was designated Swift J1931.1+1946 (Dichiara et al. 2022). Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009) reported the detection of bright X-ray emission from this location shortly thereafter (Negoro et al. 2022).

Subsequently the Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) on board Fermi reported the detection of an exceptionally bright long-duration GRB ≈55 minutes prior to the initial BAT trigger, with a consistent localization (Veres et al. 2022). Due to issues in receiving data, the automated classification and localization notices associated with this onboard GBM trigger were not distributed to the world. However, the Fermi team rapidly communicated the existence of the GBM trigger, and its spatial coincidence with the double BAT trigger, to the Swift team. This spatial association, together with analysis of prompt XRT data that showed a smooth GRB-like power-law decline, led to the conclusion that Swift J1931.1+1946 was in fact a GRB, GRB 221009A (Kennea et al. 2022). For the first time in the ∼18 yr since launch, BAT triggered not on the GRB prompt emission, but instead on the bright high-energy afterglow when GRB 221009A entered the field of view.

The unusual brightness of GRB 221009A prompted widespread follow-up at multiple wavelengths. Additional X-ray detections were reported by the Neutron Star Interior Composition Explorer (NICER; Iwakiri et al. 2022) and the Nuclear Spectroscopic Telescope Array (NuSTAR; Brethauer et al. 2022). The Large High Altitude Air Shower Observatory reported detecting photons up to 18 TeV (Huang et al. 2022). Changes in the strength of signals propagated by radio transmitters were recorded at the time of the GBM trigger as the photons from the GRB ionized Earth's atmosphere (Guha & Nicholson 2022; Schnoor et al. 2022). Spectroscopic observations of the afterglow and the host galaxy provided a redshift of $z = 0.151$ (Castro-Tirado et al. 2022; de Ugarte Postigo et al. 2022; Izzo et al. 2022), corresponding to a distance of 749.3 Mpc.

This paper is organized as follows: Section 2 contains analysis of the observations taken by Swift (BAT, XRT, and UVOT), MAXI, and NICER; in Section 3, we present analysis of the dust scattering echo, broadband spectrum, and light curve of the burst afterglow; we discuss how GRB 221009A compares to other GRBs in Section 4, investigate the astrophysical rate of similar events, and the nature of energetic GRBs; in Section 5, we present our conclusions. We show that due to the combination of proximity and large (but not unprecedented) intrinsic luminosity GRB 221009A has a much brighter X-ray afterglow than those of previously observed Swift GRBs, and such luminous nearby events are extremely rare occurrences.

For this paper, we assume a cosmology with $H_0 = 67.36$, $\Omega_m = 0.3153$, $\Omega_v = 0.6847$ (Planck Collaboration et al. 2020), and $z = 0.151$ unless otherwise stated. We adopt the GBM trigger time as the burst onset, i.e., $T_0 =$ 13:16:59.99 UTC on 2022 October 9. Magnitudes are reported on the Vega system, and uncertainties are given at a 90% confidence interval (unless otherwise noted).

2. Observations

2.1. Swift Burst Alert Telescope

Figure 1 shows the BAT raw light curves (i.e., not background subtracted), summed over all detectors, from $T_0 - 500$ s to $T_0 + 5000$ s. The location of GRB 221009A was occulted by the Earth until $T_0 + 1870$ s. At $\sim T_0 + 1100$ s, the overall count rate began to rise due to increased particle background as Swift approached the South Atlantic Anomaly (SAA). From $T_0 + 1317$–2183 s, BAT data collection was disabled as Swift transited the SAA. The count rate remained

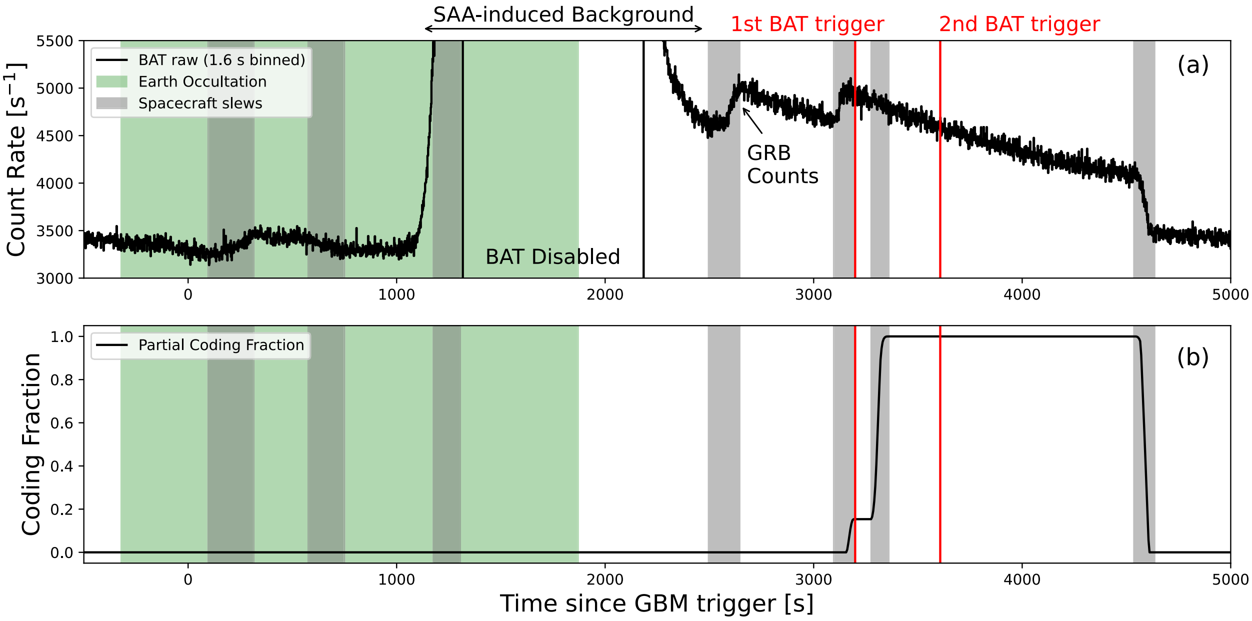

Figure 1. BAT raw light curve from the rate data. Panel (a) shows the raw light curve in the 15–350 keV band with a time binning of 1.6 s. This light curve was made from BAT quad-rate data, which records continuous count rates from all active detectors in four different energy ranges (15–25, 25–50, 50–100, and 100–350 keV). The time period when the GRB was occulted by the Earth (within 69° of the Earth center) is marked in green. Spacecraft slew times are marked in gray. The two BAT trigger times are marked by red lines. Panel (b) shows the partial coding fraction as a function of time. A partial coding fraction of 0 indicates that the GRB was outside of the BAT coded field of view, and a value of 1 indicates that the source is in the highest sensitivity region of the BAT coded field of view.

elevated while exiting the SAA until the spacecraft slew beginning at $T_0 + 2496$ s, when we attribute the linearly decaying enhanced count rate to emission from GRB 221009A. However, the source location was not in the coded portion of the BAT field of view until a slew beginning at $T_0 + 3095$ s.

Finally after this slew completed, BAT triggered on GRB 221009A, at 14:10:18 ($T_0 + 3199$ s; trigger ID 1126853) and 14:17:06 ($T_0 + 3607$ s; trigger ID 1126854) UTC. The event data from these two triggers cover a time range from $T_0 + 2960$ s to $T_0 + 4570$ s. The mask-weighted light curve shows steadily declining emission present when the burst location came into the BAT field of view at $T_0 + 3173$ s, and extending beyond the available event data range. The time-averaged spectrum from $T_0 + 3302$ s to $T_0 + 4538$ s is best fit by a simple power-law model, with $\Gamma = 2.08 \pm 0.03$. The fluence in the 15–150 keV band is $(7.4 \pm 0.1) \times 10^{-5}$ erg cm^{-2}.

The smooth temporal evolution observed by BAT, together with the large temporal offset between the BAT and GBM triggers, indicates that BAT triggered on the *afterglow* of GRB 221009A. This marks the first such occurrence of a BAT afterglow trigger in the 18 yr of Swift operations.

Given the exceptionally bright afterglow, we searched for even later emission in the BAT survey mode data using the `BatAnalysis` Python package (T. Parsotan et al. 2023, in preparation). In individual pointings of survey mode data, the afterglow was detected until 2022 October 9 21:55:38 UT ($T_0 + 31$ ks). We attempted to fit the spectra of each survey data set with a power-law (CFLUX*PO) model in XSPEC (Arnaud 1996) to obtain fluxes and photon indices. Nondetections were then analyzed to obtain 5σ upper limits following the procedure outlined in Laha et al. (2022).

At later times, the survey data were binned daily and then mosaiced together. The spectrum from each mosaiced image was fitted, and the flux and photon indices were derived similar to the procedure above. The results of this analysis are plotted in the top panel of Figure 2, and listed in Appendix A.

2.2. *Swift X-Ray Telescope*

The XRT began observing GRB 221009A at 14:13:09 UT ($T_0 + 3370$ s, 170 s after the first BAT trigger) and located a bright afterglow in the initial 0.1 s image-mode exposure, after which observations began in windowed timing (WT) mode. The initial WT count rate was 910 ± 40 ct s^{-1} (all XRT count rates are corrected for the effects of pile-up and hot columns; see, e.g., Evans et al. 2007); making it more than an order of magnitude brighter at this time—in observed flux—than any other GRB observed by XRT. Due to the high count rate, the XRT remained initially in WT mode, in which only 1D spatial information is collected. Significant structures are present in the 1D spatial profiles, with a clear excess compared to the expected point-spread function (PSF), which were evolving with time (see Appendix B). This resembles the behavior expected when dust clouds in our Galaxy scatter X-rays from the GRB prompt emission, which were not initially traveling toward Earth, back into our line of sight.

At $T_0 + 89$ ks, the GRB had faded sufficiently that the XRT automatically switched to photon counting (PC) mode. The 2D image from this observation, shown in Figure 3, confirmed the presence of a complex series of expanding, bright rings associated with a dust-scattering echo (see also Tiengo et al. 2022; Vasilopoulos et al. 2023), the properties of which are discussed in Section 3.1.

The presence of scattered emission complicates the data analysis, as it can contribute events to the regions over which source and background counts are accumulated. Both the intensity and spectrum of the rings are spatially variable; thus the selected *background* region may in fact not be representative of the background within the source region. As a result, the