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Expected Gamma-Ray Burst Detection Rates and Redshift Distributions for the BlackCAT CubeSat Mission

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Abstract

We report the results of an extensive set of simulations exploring the sensitivity of the BlackCAT CubeSat to long-duration gamma-ray bursts (GRBs). BlackCAT is a NASA APRA-funded CubeSat mission for the detection and real-time subarcminute localization of high-redshift ($z \gtrsim 3.5$) GRBs. Thanks to their luminous and long-lived afterglow emissions, GRBs are uniquely valuable probes of high-redshift star-forming galaxies and the intergalactic medium. In addition, each detected GRB with a known redshift serves to localize a region of high-redshift star formation in three dimensions, enabling deep follow-on searches for host galaxies and associated local and large-scale structures. We explore two distinct models for the GRB redshift distribution and luminosity function, both consistent with Swift observations. We find that, for either model, BlackCAT is expected to detect a mean of 42 bursts per year on orbit, with 6.7% to 10% of these at $z > 3.5$. BlackCAT bursts will be localized to an $r_{90} \lesssim 55''$ precision and reported to the community within seconds. Due to the mission orbit and pointing scheme, bursts will be located in the night sky and well placed for deep multiwavelength follow-up observations. BlackCAT is on schedule to achieve launch readiness in 2025.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Star formation (1569); X-ray telescopes (1825); Transient detection (1957); High-redshift galaxies (734)

1. Introduction

The successful launch and commissioning of JWST (Gardner et al. 2023) has provided the global astronomical community with a revolutionary new set of capabilities for studying the high-redshift Universe. As a result, from the moment of the mission's first data release, analyses have proliferated, identifying (Austin et al. 2023; Carnall et al. 2023; Finkelstein et al. 2023; Casey et al. 2024; Hainline et al. 2024; McLeod et al. 2024) and spectroscopically confirming (Arrabal Haro et al. 2023; Curtis-Lake et al. 2023; Fujimoto et al. 2023) a rich harvest of massive star-forming galaxies from redshifts $z \gtrsim 10$. These indications of vigorous early star-forming activity have been bolstered by JWST's identification of massive and merging galaxies at slightly lower redshifts of $7 \lesssim z \lesssim 10$ (Labbé et al. 2023; Boyett et al. 2024).

While the quantitative picture of this dawn of star formation remains under construction, there is already widespread agreement that star formation was underway early, energetically, and extensively well before the end of what had previously been termed the “cosmic dark ages” (Austin et al. 2023; Bouwens et al. 2023; Donnan et al. 2023; Leung et al. 2023; Wang et al. 2023; Mascia et al. 2024). In particular, there is no sign yet of a sharp cutoff to star formation in the early Universe, neither at the end of reionization at $z \approx 6$ nor at the highest redshifts of $z \approx 12$ probed to date by JWST programs.

These findings are encouraging for astronomers interested in studying early star formation by other means. Among these alternative approaches are long-duration (collapsar-type) gamma-ray bursts (GRBs): intense and highly luminous bursts of X-ray to gamma-ray radiation produced in association with the deaths of some massive stars (for a review, see Gehrels et al. 2009). Since the production of a GRB requires only a single star, GRBs are expected to occur wherever and whenever stars are being formed. And since GRBs are individually highly luminous events—both in terms of their prompt high-energy emissions and their subsequent broadband afterglows—they can be detected by relatively modest high-energy facilities out to high redshifts and studied by a broad range of astronomical facilities.

GRBs act as reliable tracers of star formation at $z \gtrsim 3$ (Greiner et al. 2015; Schulze et al. 2015; Sears et al. 2024). Since the Neil Gehrels Swift Observatory (Gehrels et al. 2004) has discovered GRBs with spectroscopic redshifts out to $z \approx 8$ (Salvaterra et al. 2009; Tanvir et al. 2009, 2018) and photometric redshifts out to $z \approx 9.4$ (Cucchiara et al. 2011), the existing burst sample already extends into the era from which JWST is collecting statistical samples of luminous star-forming galaxies.

To the extent that GRBs can be discovered at these redshifts and studied with high-quality spectroscopy, they offer several unique advantages.

First, GRBs provide a measure of star formation that is independent of host galaxy luminosity. The detectability of the burst and the brightness of its subsequent afterglow—which enables its redshift measurement—are driven by physical



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processes at stellar and subparsec scales that do not depend on the overall scale or mass of the surrounding host galaxy. As such, statistical studies of GRBs at $z \gtrsim 8$ promise to reveal the fraction of star formation occurring in galaxies too faint to be detected in even the deepest JWST fields.

Second, high-quality afterglow spectra readily yield abundance measurements for the absorbing gas along the line of sight in the GRB host galaxy. These measurements provide a means to measure metal abundances in the interstellar medium of the host galaxy. In this way, GRB afterglows can be used to probe cosmic chemical evolution. Abundance measurements using afterglow spectra can be made in galaxies of arbitrarily faint magnitude, including galaxies too faint for direct study, with the absorption-based approach offering a natural complement to common emission line-based diagnostics.

Third, afterglow spectra typically reveal absorption by neutral hydrogen along the line of sight in the host galaxy and (at redshifts preceding reionization) the intergalactic medium (IGM). The damping wing of Ly α absorption from the host galaxy provides a direct measure of the escape fraction of ionizing photons from star-forming regions f_{esc} , a crucial input to models of reionization (Chen et al. 2007; Fynbo et al. 2009). When it can be accurately characterized, the extended damping wing of Ly α absorption in the IGM reveals the IGM neutral hydrogen fraction, x_{HI} , a direct measure of the progress of reionization (Miralda-Escudé 1998; McQuinn et al. 2008; Mesinger & Furlanetto 2008; Chornock et al. 2013).

Thanks to the multifaceted promise of high-redshift GRBs, two wide-angle soft X-ray space observatories (in addition to BlackCAT) will begin searching for these objects in the near future. Like BlackCAT, these missions aim to discover and localize GRBs from $z \gtrsim 5$ and deliver prompt positions to observers, who will then seek to determine burst redshifts and exploit the burst afterglows for science. The recently launched Chinese–UK Einstein Probe (Yuan et al. 2018) uses novel “lobster eye” X-ray optics, while the Chinese–French SVOM mission (Wei et al. 2016) will, like BlackCAT, take a coded-aperture approach. SVOM promises to autonomously follow up its own burst positions in the X-ray and optical, in the style of the Swift mission, using onboard telescopes.

Any of these new satellites, or the ongoing Swift mission, could provide the burst detection that leads to the first high-redshift afterglow spectrum with JWST. As a complement to its versatile instrument suite, JWST boasts a rapid target-of-opportunity capability that enables it to observe newly identified high-priority targets within 48 hr. Assuming JWST is triggered and repointed promptly, its exquisite sensitivity should allow it to collect a high-quality spectrum of almost any high-redshift afterglow.

The present paper aims to calculate, in advance of launch, the detection rate and redshift distribution of BlackCAT long-duration GRBs. This will allow the mission science team, along with interested observers, to appropriately scope proposals and efforts for mission follow-up programs.

The next section (Section 2) presents the design and capabilities of the BlackCAT mission. We discuss our simulations of GRB populations and BlackCAT burst detection in Section 3 and report the results of our simulations in Section 4. Our conclusions are presented in Section 5.

2. The BlackCAT CubeSat

The Black Hole Coded Aperture Telescope, or BlackCAT, is a 6U CubeSat mission designed to search for high-redshift GRBs, multimessenger source counterparts, and other X-ray transient phenomena. It will also serve as a wide-field monitor to identify flaring states of galactic X-ray binaries and active galactic nuclei. BlackCAT will be a pathfinder and technology test bed for a future larger mission or larger array of similar CubeSats that will increase the overall effective area and field of view (FOV). BlackCAT boasts a wide FOV (0.85 sr partially coded) and soft X-ray bandpass (0.5–20 keV) that supplement existing on-orbit capabilities and make it a powerful new tool for transient and time-domain astronomy. With a coded-aperture pitch of 320 μm and a focal distance of 15.8 cm, GRBs and high-significance transients will be localized to $r_{90} \lesssim 55''$ (90% confidence localization radius), enabling high-sensitivity follow-up observations by most astronomical facilities. Real-time burst alerts will be transmitted to the ground via the Iridium satellite network and distributed via NASA’s General Coordinates Network (GCN⁴). Complete mission data, including all high-quality X-ray events, will be telemetered at least twice daily following ground station passes over Svalbard, Norway. Models of the science instrument and spacecraft are shown in Figure 1, and key mission parameters are summarized in Table 1.

The mission’s scientific instrument is a coded-aperture X-ray telescope with an array of four X-ray hybrid CMOS detectors (HCDs) in the detector plane. A similar X-ray HCD was flown on the Water Recovery X-Ray Rocket mission in 2018 (Miles et al. 2019); BlackCAT will provide the detectors’ first use on a satellite. Validating and characterizing the long-term in-space performance of Speedster-EXD550 HCDs is the primary technology-development driver for BlackCAT.

The active-pixel nature of the Speedster HCDs enables ultrafast readout, with frame rates in excess of 150 Hz (Colosimo et al. 2023). The detectors are also capable of event-driven readout, in which only pixels with sufficient signal are read out, allowing for even faster effective readout speeds.

The coded mask will be manufactured by Luxel and constructed from gold-plated nickel. The mask is composed of open and closed elements, each a square 320 μm on a side. Closed elements have a 25 μm thick layer of metal (17 μm of nickel and 8 μm of gold), while open elements have no metal. The closed cells will attenuate X-rays with energies $E_\gamma \lesssim 20$ keV and so impose the mask pattern onto the received flux in the detector plane. The walls of the detector module are designed to block off-axis X-rays below 20 keV. The pattern of the mask was randomly generated, with $\sim 50\%$ of cells open. A thin-film filter composed of aluminum and polyimide behind the mask will prevent optical and ultraviolet light from reaching the focal plane detectors.

BlackCAT will serve as a potential pathfinder mission for future missions targeting X-ray detections of high-redshift GRBs. These could incorporate multiple BlackCAT coded-aperture modules on a single platform or consist of an array of separately flying CubeSats. Such missions could potentially offer both increased sensitivity and increased coverage relative to BlackCAT.

⁴ GCN website: <https://gcn.nasa.gov/>.

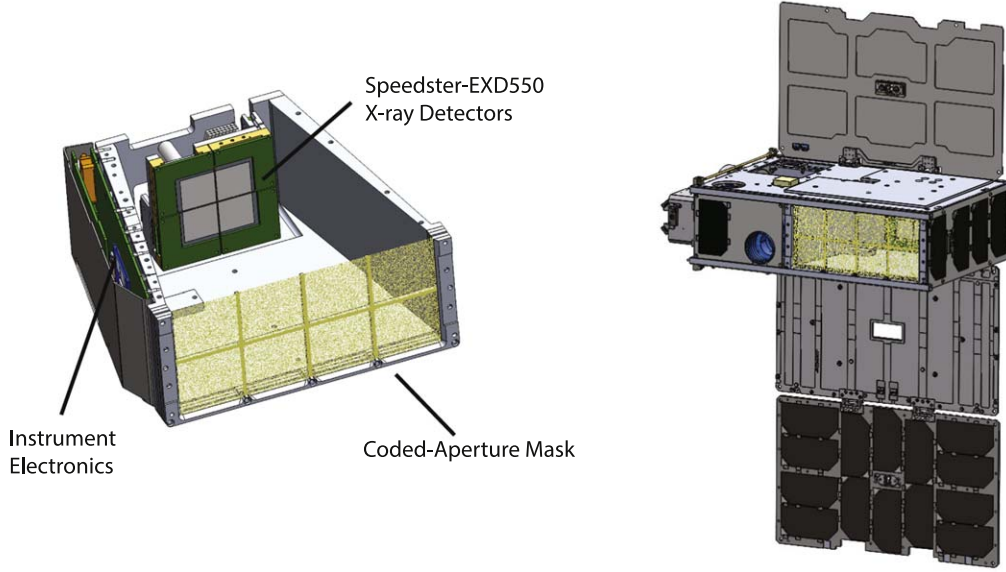


Figure 1. Computer renderings of the coded-aperture telescope instrument on BlackCAT (left) and of the BlackCAT CubeSat with solar panels deployed as on orbit (right).

Table 1
Design and Performance Parameters for the BlackCAT CubeSat

Parameter	Value
Platform	6U CubeSat
Energy Band	0.5–20 keV
Effective Area	7.7 cm ² at 5 keV
Field of View	0.85 sr (partially coded)
Source Localization	40'' to 55'' (r_{90})
Duty Cycle	~76%

BlackCAT will be launched into a dawn–dusk Sun-synchronous orbit at a fixed altitude of $h \approx 550$ km. This orbit will provide near-continuous illumination of the solar panels and allow the radiator, responsible for cooling the focal plane detectors, to be stably oriented to minimize exposure to solar and terrestrial radiation. In this orientation, the telescope will maintain a near anti-Sun pointing throughout each orbit. Bursts detected by BlackCAT will therefore be located in the night sky, enabling prompt follow-up observations from ground-based observatories.

On orbit, the observatory will operate in a stepwise stare mode, with the instrument maintaining a stable pointing for approximately 10 minutes at a time before slewing to maintain its relative orientation to the Earth and Sun. Each $\approx 40^\circ$ slew will take roughly 1 minute. During slews, the instrument will not trigger on bursts; however, X-ray data will be acquired while the instrument is slewing and saved for transmission to the ground. Analyses of these data are subject to increased pointing uncertainty due to the active slew. In our mission simulations, we treat the entirety of slew durations as downtime, leading to a 9.7% reduction in duty cycle.

Apart from these active slew periods, mission simulations account for a further reduction in duty cycle due to periods of high particle background expected at high latitudes and during passages through the South Atlantic Anomaly. Using estimates of the duty cycle from Colosimo et al. (2022), we expect the satellite to be passing through such regions for 16% of each orbit. While the instrument will operate continuously during

these periods, it will have significantly reduced sensitivity that will limit the number of transient detections. Although strict event cuts may enable the detection of relatively bright bursts during these periods, for the present purposes we adopt the full 16% reduction in duty cycle. Combining the effects of active slews and high particle background yields a 76% duty cycle for these simulations.

3. Simulations and Analysis

3.1. GRB Population Simulations

We begin by modeling the long-duration (collapsar-type) GRB population distribution in redshift and luminosity. We use the population of GRBs observed by Swift to constrain these models. Redshift measurements are necessary to constrain population models, so only those bursts whose redshifts have been reported by follow-up observers are used in this analysis. We use the table of Swift long GRBs with measured redshifts compiled by Lan et al. (2021), hereafter L+21.

We model the GRB luminosity function as a broken power law,

$$\phi(L) = \begin{cases} A \left(\frac{L}{L_0} \right)^{-\alpha}, & L \leq L_0 \\ A \left(\frac{L}{L_0} \right)^{-\beta}, & L > L_0 \end{cases}, \quad (1)$$

where the coefficient A normalizes the distribution for a low-luminosity cutoff at $\log L = 49$ ($L = 10^{49}$ erg s^{−1}). We model the intrinsic GRB redshift distribution using the cosmic star formation rate (CSFR) of Madau & Dickinson (2014):

$$\psi_*(z) = 0.015 \frac{(1+z)^{2.7}}{1 + [(1+z)/2.9]^{5.6}} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}. \quad (2)$$

The long GRB rate is related to this CSFR $\psi_*(z)$ by an efficiency factor, $\eta(z)$. This efficiency factor is required to evolve with redshift to account for the accelerated evolution of the GRB rate at low redshifts, $z < 3$, compared to the CSFR.

Table 2
Parameters of the Swift GRB Redshift Distribution and Luminosity Function, as Derived from Our Maximum Likelihood Fits

Model	η_0 ($10^{-8} M_\odot^{-1}$)	δ	$\log L_0$ (erg s^{-1})	α	β
Weak Evolution	$4.52^{+1.17}_{-0.94}$	$1.92^{+0.27}_{-0.26}$	$53.06^{+0.34}_{-0.13}$	$1.61^{+0.06}_{-0.06}$	$2.71^{+0.70}_{-0.30}$
Strong Evolution	$5.02^{+1.25}_{-1.00}$	$1.88^{+0.22}_{-0.21}$	$53.02^{+0.16}_{-0.12}$	$1.63^{+0.06}_{-0.05}$	$2.67^{+0.41}_{-0.26}$

Note. Parameter median values are quoted along with $\pm 1\sigma$ confidence intervals.

This evolution is well established (Kistler et al. 2008; Vergani et al. 2015; Palmerio et al. 2019) and reasonably attributed to metallicity effects, which reduce the fraction of GRB progenitors among massive stellar populations at higher metallicity in the low-redshift Universe (Heger et al. 2003; Yoon & Langer 2005; Stanek et al. 2006; Woosley & Heger 2006). Adopting a power-law form for the differential evolution of collapsar-type GRBs, we write (see also L+21):

$$\psi(z) = \eta(z)\psi_*(z) = \eta_0 (1+z)^\delta \psi_*(z), \quad (3)$$

where the exponent δ serves as the differential evolution parameter.

We investigate two different approaches to the evolution of $\eta(z)$. The first, which we term “weak evolution,” has $\eta(z)$ increasing to a maximum at $z = 3$ and then remaining fixed for all higher redshifts $z > 3$. The second, which we term “strong evolution,” allows $\eta(z)$ to increase without bound as z increases.

The case for weak evolution rests on the metallicity argument for differential evolution at low redshift, along with observations of $z > 3$ GRB host galaxies (Greiner et al. 2015; Schulze et al. 2015; Sears et al. 2024), which are consistent with these host galaxies being drawn (as weighted by galaxies’ star formation rates) from the star-forming galaxy population.

The case for strong evolution rests on previous phenomenological fits, including those of L+21, which find that continued differential evolution of the GRB rate at $z > 3$ provides a better fit to the Swift GRB luminosities and redshifts. In addition, we note that if recent JWST results mean that the CSFR at $z > 5$ (Equation (2)) has previously been underestimated, this could lead to GRB studies finding continued differential evolution relative to those models. That is, continued differential evolution at $z > 5$ might mean that the GRB-based approach is more accurately revealing the true CSFR at these redshifts. Alternatively, it may mean that additional factors, for example an evolving initial mass function or an evolving jet opening angle (Lloyd-Ronning et al. 2020), continue to increase the GRB efficiency $\eta(z)$ to high redshifts, leading to continued differential evolution relative to the CSFR.

We use a maximum likelihood method, as in L+21, to estimate parameters for both weak and strong evolution models. To fit the observed Swift sample we must account both for Swift sensitivity and for the incomplete nature of redshift recovery efforts. We model Swift sensitivity using a threshold peak flux of 1 photon $\text{cm}^{-2} \text{s}^{-1}$ in the Swift Burst Alert Telescope (BAT) band (15–150 keV). This is a common approach; nearly all bursts with peak fluxes above this threshold are detected by Swift, and the L+21 sample includes 302 bursts with peak fluxes exceeding this threshold.

We model the probability of redshift measurement as a function of peak photon flux using Equation (1) from L+21. In

this model, the probability of redshift recovery is near 100% for bright bursts and has a floor of $\approx 32\%$ for faint (near threshold) bursts. The redshift recovery probability increases in a sigmoid-like fashion as the peak flux increases from 10 to 100 photons $\text{cm}^{-2} \text{s}^{-1}$ (15–150 keV).

We replicate the parameter estimation from L+21 using their two-segment power-law luminosity function, reproducing the results for their “no evolution” and CSFR evolution models; note that L+21 uses a CSFR model from Li (2008). We find best-fit parameters consistent with theirs.

We carry out maximum likelihood fits for the weak and strong evolution models described above, with best-fit model parameters and confidence intervals as reported in Table 2. Parameter confidence intervals are derived from the 68th percentile distributions of the Markov Chain Monte Carlo samples. Figure 2 presents our model fits along with histograms of the Swift burst data. Consistent with L+21 and other previous analyses (e.g., Wanderman & Piran 2010; Ghirlanda et al. 2015; Pescalli et al. 2016), we find an adequate fit with a nonevolving luminosity function under either weak or strong evolution. We find that the strong evolution model better accounts for the few highest-redshift Swift GRBs, which is also consistent with previous analyses. The only noticeable deficiency in the fits, visible in the luminosity histogram, is the excess of observed GRBs at low luminosities ($L < 10^{50} \text{ erg s}^{-1}$) compared to the models. As investigated by L+21, a three-segment power law can account for this low-luminosity excess; however, since our present simulations are focused on the detectability of high-luminosity high-redshift bursts, we do not further explore this possibility here. We may explore the sensitivity of BlackCAT to low-luminosity GRBs at $z < 1$ in future work.

3.2. Light-curve Simulations

We use Swift BAT light curves as templates for our simulations. This allows us to capture the diversity and complexity of the burst population and accurately assess the anticipated performance of the instrument and flight software. All Swift BAT light curves and spectral fits used here were retrieved from the Swift Burst Analyser⁵ (Evans et al. 2010). We use the time-integrated t_{90} spectral models (power law or cutoff power law) and the corresponding light curves with fixed spectral parameters, both analyzed over the 15–50 keV band.

To create a simulated GRB light curve, a luminosity and redshift are drawn randomly from their respective distributions using the models developed above. We sample luminosities over the range $50 < \log L < 56$ and redshifts up to $z = 30$. While we fit the burst luminosity function down to $\log L = 49$, we find that—without an additional power-law component at low luminosities—bursts below $\log L = 50$ do not contribute

⁵ Swift Burst Analyser: https://www.swift.ac.uk/burst_analyser/.

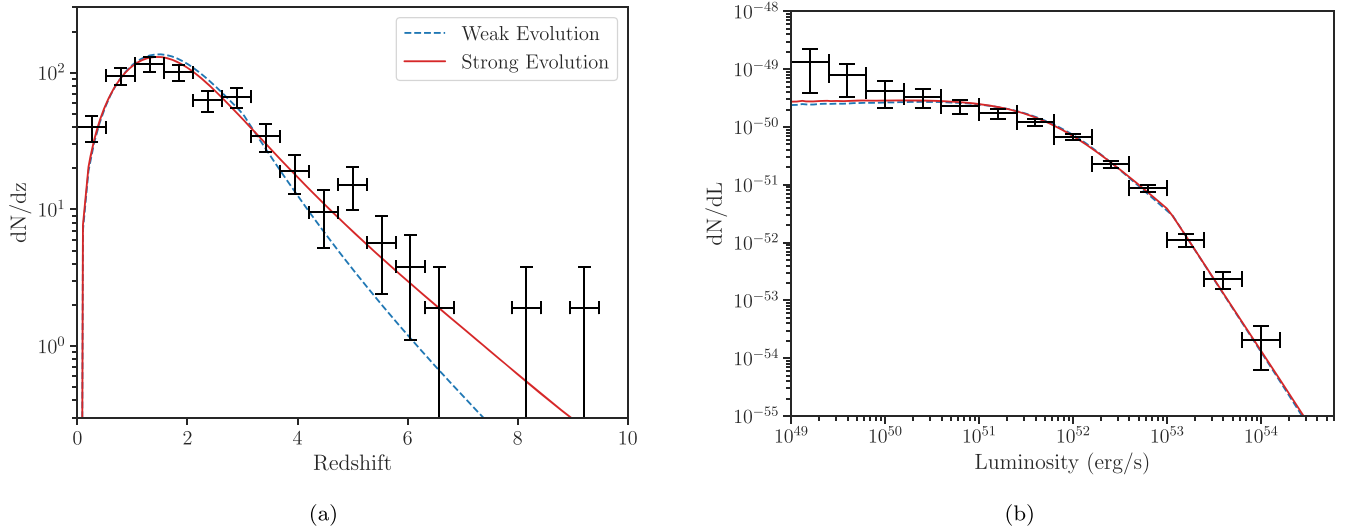


Figure 2. Redshift and luminosity distributions of Swift BAT GRBs with measured redshifts and peak fluxes $P > 1 \text{ photon cm}^{-2} \text{ s}^{-1}$. The plotted curves show our model fits for weak evolution (dashed) and strong evolution (solid) models. Bursts for this analysis are drawn from Table A1 in L+21, corresponding to 15 yr worth of Swift BAT observations.

meaningfully to the rate of detected bursts for BlackCAT. Likewise, bursts beyond $z = 30$ are not expected to be detected by BlackCAT due to the low modeled rate above this redshift and the large luminosity distance. Template Swift bursts are drawn from the full sample of 424 long GRBs in L+21, including bursts with peak fluxes $P < 1 \text{ photon cm}^{-2} \text{ s}^{-1}$, which are excluded from the model fits. Each template burst is selected randomly from the 10 bursts in the table with luminosities nearest to the desired luminosity for the simulated burst.

The timescale of the light curve is scaled by $(1+z)$ to account for cosmological time dilation, and the burst flux is scaled to account for the new luminosity, luminosity distance, and K-correction (bandpass effects). We use standard cosmological parameters of $h = 0.7$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ in our analysis. The cutoff energy in cutoff power-law models is also adjusted for redshift when applicable. The scaled spectral model is then used to calculate the flux for each time interval in each of the defined BlackCAT trigger bands.

3.3. Burst Detection Simulations

BlackCAT will run a series of imaging triggers, based on its flight software heritage from Swift BAT. The set of triggers will consider a wide range of timescales and energy bands to detect bursts with a variety of durations and spectral energy distributions. Our simulations include 70 triggers, covering 7 timescales ranging from 0.125 to 64 s and 10 energy ranges within the detector bandpass of 0.5–20 keV. A similar set of triggers will be used in the flight software to identify bursts and provide rapid alerts to the ground. Candidate bursts will be compared to an onboard catalog of known X-ray sources and reported if no counterpart is identified.

We use our simulated light curves to model the response of these burst triggers and determine the rate and distribution of bursts observable by BlackCAT. The simulated bursts are distributed uniformly over the entire (partially coded) FOV. Burst counts are sampled from the light curve in the various BlackCAT energy bins and fed through the BlackCAT response function to create a list of photon detections and energies.

We estimate the background from the diffuse X-ray background and bright astrophysical sources using MAXI Solid-state Slit Camera (SSC; Matsuoka et al. 2009) all-sky X-ray maps from Nakahira et al. (2020). Outside of the MAXI-SSC bandpass, we model the cosmic X-ray background as a broken power law based on Comastri et al. (1995) and Moretti et al. (2009). We smooth the MAXI-SSC maps on the scale of the BlackCAT FOV to estimate the background rate for a given pointing. While not strictly correct, this approach is accurate in the mean and significantly streamlines our simulation effort.

Figure 3 shows a simulated map of BlackCAT exposure after one year on orbit for one template launch date and observing strategy. Locations of the brightest X-ray sources from the MAXI Gas Slit Camera (GSC) catalog are indicated. Pointings that include the central portions of the Galactic plane and/or bright persistent sources such as Sco X-1 and the Crab Nebula will exhibit reduced sensitivity to transients. However, by the same token, these pointings will enable the mission to monitor the state of Galactic X-ray binaries and other high-energy sources and provide community alerts when these sources flare or change state.

We use the burst counts and background count rate for the selected pointing to simulate detector pixel counts over the timescales and energy ranges defined by the various burst triggers. Sky images are constructed by deconvolving the detector pixel counts with the mask pattern. Peaks in the image are identified; those in excess of the 6.5σ threshold (relative to nearby background fluctuations) are treated as candidate bursts.

On orbit, candidate burst localizations will be compared to a catalog of known X-ray sources. If no corresponding source is identified in the catalog, a burst alert will be relayed to the ground. BlackCAT burst alerts will report preliminary information about the location, brightness, and duration of each burst.

4. Simulation Results

We simulate 100 yr of bursts, under both weak and strong evolution scenarios, in order to minimize the impact of Poisson fluctuations on our reported per-year burst rates. Detected burst rates are scaled by a factor of 0.76 to account for the estimated

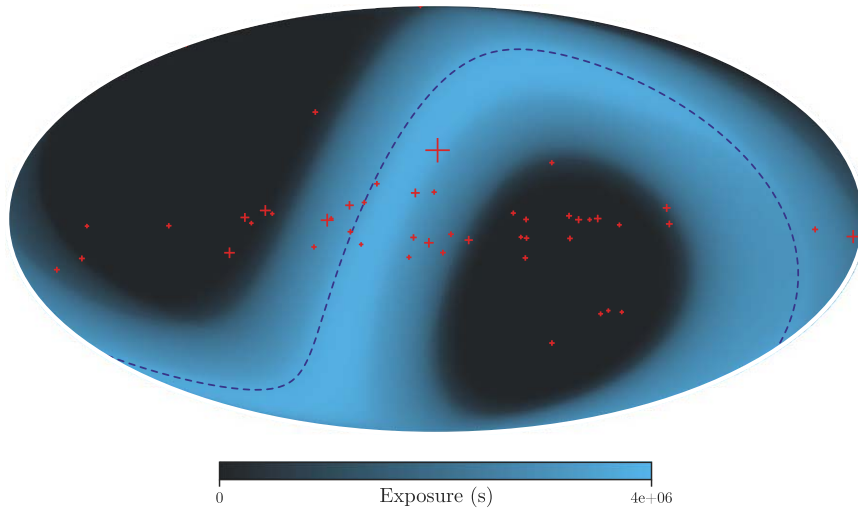


Figure 3. Simulated 1 yr BlackCAT exposure map in Galactic coordinates for a nominal anti-Sun pointing plan. Bright X-ray sources from the MAXI/GSC 7 yr High and Low Galactic Latitude Source Catalogs (Hori et al. 2018; Kawamuro et al. 2018) are shown in red, and the equatorial plane is indicated by the dashed purple line. Periods during which BlackCAT observes the Galactic plane will yield reduced sensitivity to GRBs while enabling daily monitoring of bright Galactic X-ray sources.

duty cycle on orbit. As discussed in Section 2, the mission duty cycle is reduced by active slews and passage through regions of high particle background.

We find that the total rate of BlackCAT burst detections varies by $<3\%$ across the weak and strong evolution scenarios. Under the weak evolution scenario, we find a BlackCAT detection rate of 41.7 bursts per year, whereas in the strong evolution scenario it is 43.0 bursts per year. The redshift distribution of detected bursts is shown in Figure 4, with burst rates over several illustrative redshift ranges provided in Table 3. The continuing differential evolution of the GRB rate at $z > 3$ in the strong evolution scenario leads to a $+50\%$ increase in the burst rate at $z > 3.5$ and a $\times 2$ increase in the burst rate at $z > 5$.

We find that maintaining a large number of triggers is important in maximizing BlackCAT’s detection rate. No individual trigger provided the highest-significance detection for a majority of detected bursts under either scenario. Moreover, nearly every evaluated trigger provided the highest-significance alert for at least one burst out of those simulated. This reaffirms our plan to use a range of triggers in the flight software for real-time burst detection. Evaluation of a wide range of triggers will also be useful for various secondary mission goals, including detection of short-duration (merger-type) GRBs.

The planned Sun-synchronous polar orbit and anti-Sun orientation of BlackCAT mean that detected bursts will be well positioned for prompt and extended follow-up by ground-based observatories. Nearly all bursts will lie within the field of regard of the Hubble Space Telescope, and roughly three-quarters will lie within the Vera Rubin Observatory (VRO) survey area. Bursts within the VRO survey area, effectively all of those south of $+15^\circ$ decl., will be subject to deep multiband observation according to its ≈ 4 day survey cadence. The JWST field of regard includes a broad anti-Sun exclusion zone which reduces overlap with BlackCAT baseline pointings; we estimate that $\approx 9\%$ of BlackCAT bursts will be immediately accessible to observation with this facility. It is possible that the fraction of BlackCAT bursts accessible to JWST observation could be increased by carefully considered adjustments to the baseline pointing plan.

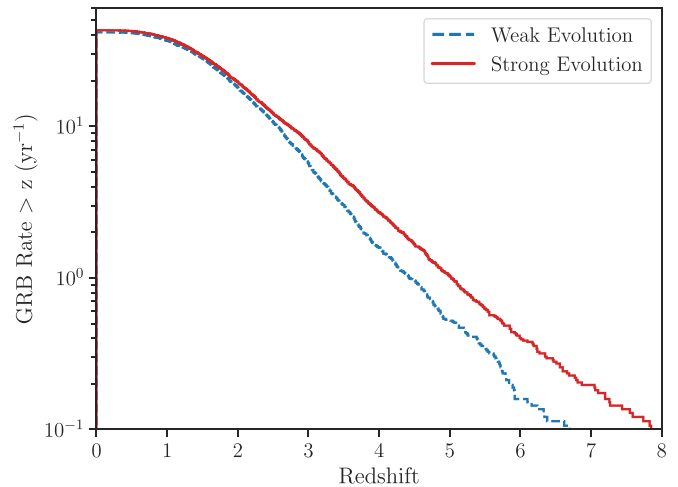


Figure 4. Cumulative redshift distribution of GRBs detected by BlackCAT for the weak and strong evolution scenarios. The rate is given as the number expected, per year on orbit, above a given redshift. Numbers are drawn from our 100 yr simulations.

Table 3
Burst Detection Rates (yr^{-1}) on Orbit under Weak and Strong Evolution Scenarios

Model	All Bursts	$z > 3.5$	$z > 5$	$z > 6.5$	$z > 8$
Weak Evolution	41.7	3.02	0.53	0.11	0.04
Strong Evolution	43.0	4.54	1.02	0.28	0.09

5. Conclusions

In order to anticipate the GRB detection rate and redshift distribution of long-duration (collapsar-type) bursts that will be detected by the BlackCAT CubeSat mission, we have carried out an extensive set of burst simulations.

Using a catalog of long-duration GRBs with known redshifts detected by Swift, as tabulated by L+21, we fit for the GRB redshift and luminosity distribution under two scenarios for their differential evolution relative to cosmic star formation. In the weak evolution scenario, differential evolution is present only for $z < 3$, whereas in the strong evolution scenario,

differential evolution continues to increase the efficiency of GRB production relative to cosmic star formation out to the highest redshifts.

Our findings are consistent with previous analyses of these effects, including L+21. The GRB rate exhibits differential evolution relative to the CSFR (Madau & Dickinson 2014) with an exponent $\delta \approx 1.9$ in $(1+z)$. A two-segment power-law luminosity function provides a satisfactory fit, apart from a mild excess of low-luminosity bursts over the range $49 < \log L < 50$, which we do not consider relevant to our exploration of BlackCAT observations of high-luminosity, high-redshift bursts. While the strong evolution model more readily accommodates the highest-redshift Swift GRBs (Figure 2), the fit for weak evolution models is nonetheless satisfactory, and its predictions provide a conservative lower bound for our purposes.

Our model fits to the GRB population, along with light-curve and spectral information for Swift bursts, allow us to simulate the on-orbit performance of the BlackCAT coded-aperture telescope and flight software. We account conservatively for expected on-orbit backgrounds, including bright X-ray sources, and adjust the expected duty cycle for periods of active slewing and passage through regions of high particle background. We simulate burst and background counts in detector pixels, deconvolve with the detector mask pattern, and identify peaks in sky images using prototype flight software. For each of the weak and strong evolution scenarios, we simulate 100 yr on orbit to minimize uncertainties in reported burst detection rates.

We find that, for an assumed on-orbit duty cycle of 76%, BlackCAT will realize a long-duration GRB detection rate of 42 bursts per year as the expected mean rate for a Poisson distribution. Of these bursts, 6.7% (weak evolution) to 10% (strong evolution) are expected to have redshifts $z > 3.5$. Figure 4 and Table 3 summarize our results.

BlackCAT bursts will be localized on board to $\lesssim 55''$ precision and reported to ground-based observers within seconds via Iridium satellites and NASA's GCN. The combination of arcminute-scale localizations, timely alerts, and night sky locations will make BlackCAT bursts excellent targets for rapid and intensive follow-up observations across the electromagnetic spectrum.

BlackCAT is currently on schedule to achieve flight readiness in 2025. After launch and two months of commissioning, the observatory will carry out a 1 yr science mission. Continuation of operations beyond that point will be possible; the mission has no consumables and its orbital lifetime is expected to be approximately 10 yr.

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Facilities: Swift (BAT), MAXI

Software: astropy (Astropy Collaboration et al. 2013, 2018).

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