OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

Target-of-Opportunity Programs at Steward: Rapid-response Observations of Gamma-ray Bursts

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Abstract of Scientific Justification

Since its launch in 2004, the *Swift* satellite has discovered gamma-ray bursts (GRBs) at a rapid rate of ≈ 2 events per week, providing positions with $\lesssim$few arcsecond precision within minutes of burst discovery. Rapid-response ground-based observations have proved to be a crucial supplement to *Swift* observations, enabling the prompt localization of GRB afterglows to sub-arcsecond precision, thereby providing redshifts, energy scales, and associations to host galaxies. In particular, the combination of optical and near-IR observations on large telescopes has led to the identification of nearly all afterglows for short GRBs, uncovered a subset of long GRBs heavily obscured by dust ("dark" GRBs), and revealed long GRBs which originate at reionization redshifts of $z\gtrsim 6$. In addition, the discovery of a near-IR transient following a short GRB ("kilonova") provided smoking gun evidence linking short GRBs to their progenitors. Here, we propose to capitalize on the sensitivity afforded by Steward's large telescopes equipped with optical/near-IR instruments to continue to develop a concerted set of Target-of-Opportunity programs with the LBT, MMT, and UKIRT, which will provide observations of GRB afterglows starting $\lesssim$1 day-1 week after burst discovery. With these programs, we will focus on four high-impact frontiers in GRB science that are well-matched to the capabilities of these large facilities: short GRBs, near-IR kilonovae, dark GRBs, and high-redshift GRBs ($z\gtrsim 6$). The observations from this program will impact studies of short GRB (and thus compact object merger) redshifts, electromagnetic counterparts to gravitational waves, obscured star formation across a wide range of redshifts, and the epoch of reionization.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	UKIRT		WFCAM,UIST,UFTI			1.5	bright	Aug-Jan	Aug-Jan	yes	yes
2	LBT	PF	LBC, MODS			0.5	bright	Aug-Jan	Aug-Jan	yes	yes
3	MMT	f/5	MMTCam			1	bright	Aug-Jan	Aug-Jan	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*:

Observations will be spread throughout the semester with $\lesssim$1 day of notice in most cases. Exact timing and sequence observations will depend on the nature of the target and which facilities are available. Since GRBs can occur at any time, there are no constraints on weather conditions or moon brightness. More details are in the experimental design section.

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A $\star$ appended to the proposal type indicates a continuation proposal; a $\star$ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a $*$ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	GRB1	00:00:00	00:00:00	Target-of-Opportunity

Approval for Instrument Use from PI: _____

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

1. Motivation: The Importance of Target-of-Opportunity Programs

Gamma-ray bursts (GRBs) are cosmic explosions which release $\approx 10^{51}$ erg of energy in gamma-rays within a matter of minutes. They are divided into two classes based on the duration of their gamma-ray emission: long GRBs (duration $\gtrsim$2 sec) which result from the deaths of massive stars, and short GRBs (duration $\lesssim$2 sec), which likely originate from the mergers of two compact objects. Immediately following the prompt gamma-ray emission is the long-wavelength "afterglow" which results from the burst interaction with the surrounding medium, and is in principle detectable in radio through X-ray bands. In particular, the detection of the afterglow at optical and near-IR wavelengths allows for positions with sub-arcsecond precision, thus enabling the determination of burst redshifts, energy scales, and unambiguous associations to host galaxies. The afterglow brightness quickly fades in all bands, with a typical decline in flux $\propto t^{-1}$. Thus, *the only route to understanding both the origin and explosion properties of GRBs is through the prompt identification and monitoring of their afterglows by observations starting at* $\lesssim$1 *day after burst discovery.*

The *Swift* satellite is the main workhorse for GRB discovery and localizes $\approx 80\%$ of bursts to $\approx$few arcsec through the detection of an X-ray afterglow. The optical imager on-board *Swift* detects afterglows for only $\approx 30\%$ of bursts, necessitating ground-based optical/near-IR follow-up observations on more sensitive facilities to precisely localize the majority of events, and to monitor the afterglow evolution on timescales of $\gtrsim$1 day. Therefore, rapid-response Target-of-Opportunity (TOO) programs, which allow facilities to disrupt planned schedules to observe the location of the GRB, provide a crucial supplement to *Swift* observations.

Indeed, the past decade of TOO observations has revolutionized our understanding of GRBs. In particular, the combination of optical and near-IR observations on 4-10-meter class telescopes has revealed a population of optically "dark" GRBs which are heavily obscured by dust, and uncovered a handful of events originating in the era of reionization at $z\gtrsim6$. Furthermore, such facilities have enabled the detection of nearly all short GRBs afterglows, which are fainter by a factor of $\gtrsim$10 from their long-duration counterparts, providing critical clues to the nature of their progenitors.

Here, we propose to take advantage of Steward's access to large telescopes equipped with optical/near-IR instruments to develop a concerted set of TOO programs with the LBT, MMT, and UKIRT. This proposal represents the continuation of the previously-approved TOO program in 2015A (PI: Fong). All observations from these programs will be reduced, analyzed, and rapidly disseminated to the GRB community in real time. We also have directly complementary TOO programs in the radio (VLA) and X-ray (XMM-Newton, Chandra) bands dedicated to GRB afterglows, and host galaxy follow-up programs on Steward facilities (proposed for 2015B, PI: Fong), which will provide stellar population properties. Our group is thus in a unique position to provide a comprehensive analysis of every event. We note that due to the rapid response required to obtain useful observations, this program is distinct from the AZTEC transient program (PI: Smith), which targets more slowly-evolving transients on $\sim$week-month timescales. Additionally, we intend for this set of programs to put Steward at the forefront of rapid time-domain studies, in advance of the eras of gravitational wave discovery and LSST.

2. Key Science Aims

We select four frontiers of GRB science that are both impactful and well-matched to the capabilities of LBT, MMT, and UKIRT.

a. Identifying short GRB afterglows: Only $\approx 30\%$ of short GRBs detected by the *Swift* satellite have detected optical afterglows. This is primarily due to the faintness of their optical afterglows (≈ 23 mag at 10 hr after the burst), which limits effective ground-based observations to large telescopes on timescales of $\lesssim$few days. However, optical afterglows are crucial to identify because they are the primary way to localize bursts to their host galaxies, allowing for the determination of redshifts and a wealth of additional stellar population properties (see Steward host galaxy proposal; PI: Fong). Furthermore, the sub-arcsecond

localization uniquely afforded by the detection of an optical afterglow provides the precise location of the burst within its host galaxy. Here, we propose to use our TOO programs for the rapid identification of optical afterglows in short GRBs. We initiated rapid TOO observations in January 2015 to successfully identify the optical afterglow of the short GRB 150101B (Fig. 1), which provided a robust association to an elliptical host galaxy at $z = 0.134$. The burst was located outside of the majority of its host galaxy stellar light, at a separation of 7.35 ± 0.07 kpc. At $z = 0.134$, GRB 150101B is one of the most nearby short GRBs to date.

b. Electromagnetic counterparts to gravitational waves: Advanced LIGO, slated to begin operations in late 2015, will detect the first gravitational waves from compact object mergers, but will provide poor positions with uncertainties of $\gtrsim$100 sq. deg. A coincident signal at electromagnetic wavelengths will provide sub-arcsecond localization, association to host galaxies, and redshifts. While short GRB afterglows are likely signals from compact object mergers, only a small fraction may have their jets pointed toward Earth. A more promising predicted signature of compact object mergers is isotropic emission from the radioactive decay of heavy elements created in the merger ("kilonova") predicted to peak in the near-IR on $\sim$ 1-week timescales [1]. The detection of a near-IR kilonova following the short GRB 130603B provided the first "smoking gun" linking a short GRB to a compact object merger progenitor [2] . Kilonovae have otherwise escaped detection in the past since most searches were optimized in the optical bands, or in the near-IR on timescales of $\lesssim$1 day after the bursts. Therefore, we will use a combination of late-time optical and near-IR observations following short GRBs on $\sim$ 1-week timescales to establish the brightness distribution of kilonovae prior to and during Advanced LIGO operations.

c. Obscured star formation: Since long GRBs originate from massive stars, they can be used to probe star formation across a wide range of redshifts. A subset of long GRBs have suppressed optical (and sometimes near-IR) emission relative to their X-ray afterglow brightness (termed "dark" GRBs) that cannot be explained by a high-redshift origin (see next section). A comparison of the optical/near-IR afterglow colors to the expected spectral slope for afterglows has revealed some of these bursts to have substantial amounts of extinction in their rest-frame (A_V), indicative of a region of obscured star formation. In some cases, the combination of deep upper limits on the optical/near-IR afterglows and the detection of a radio afterglow have led to large inferred values of $A_V \approx$ 5-10 mag. For example, we helped to initiate a radio through X-ray observational campaign of the afterglow of the dark GRB 110709B, where we inferred $A_V \approx$ 4-10 mag, where near-IR limits of $\gtrsim$19-21 mag provided the most stringent constraints on the extinction (Fig. 2; [4]). Thus, it is essential to use coordinated optical, near-IR, and radio observations to uncover additional bursts with moderate to significant extinction ($A_V \gtrsim 3$ mag). These studies, in conjunction with host galaxy follow-up observations, will help to localize regions of obscured star formation and constrain the fraction that contributes to the overall star formation budget.

d. Epoch of reionization: One of the last uncharted astrophysical epochs is the time between recombination and the end of the first phase of star formation. This period is referred to as reionization because much of the universe is ionized by photons generated by the first massive stars and quasars. Long GRBs are bright UV continuum light sources that make excellent probes of the degree of ambient ionization. High-redshift GRBs can be identified by the strong suppression of emission due to Lyman-α absorption by neutral hydrogen at wavelengths of $\lesssim 1216(1 + z_{\rm GRB})$ Å, thus creating a sharp spectral break. Spectroscopy of high-redshift GRB afterglows can also provide information on the metal enrichment of the host galaxy. In the absence of extinction, optical observations alone are sensitive to GRBs out to $z \approx 6$, while the addition of near-IR observations extends this sensitivity to $z \approx 9$ (J-band) and $z \approx 17$ (K-band). Thus, a combination of optical and near-IR observations are crucial in identifying GRBs at $z \gtrsim 6$. This is highlighted in the case of GRB 120521C, where the sudden emergence of the afterglow between I and z-bands, together with UKIRT detections led to a photometric redshift of $z \approx 6.0$ (Fig. 3; [3]). This approach has been used to discover all six GRBs at $z \gtrsim 6$. *Strikingly, UKIRT TOO observations played an integral role in four of these cases.* As the sample of high-redshift GRBs comprises only six events, the detection of even one additional event at these redshifts will enable significant progress in reionization studies.

References

[1] J. Barnes & D. Kasen. *ArXiv*, Mar 2013.
[2] E. Berger et al. *ApJ* , 774:L23, Sep 2013.
[3] T. Laskar et al. *ApJ* , 781:1, Jan 2014.
[4] B. Zauderer et al. *ApJ* , 767:161, Apr 2013.

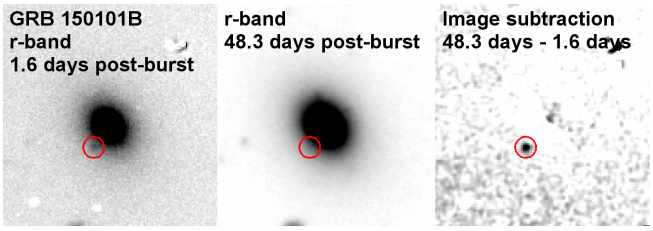

Figure 1: Rapid optical TOO observations of the afterglow of short GRB 150101B obtained in January 2015 with Magellan/IMACS at two separate epochs: 1.6 and 48.3 days after the burst. Image subtraction reveals a faint optical afterglow (red circle) with $r \approx 23.01 \pm 0.17$ mag. While the afterglow itself faded too quickly to extract a redshift, it provides sub-arcsecond localization and therefore a robust association to an elliptical host galaxy at $z = 0.134$. GRB 150101B is among the most nearby short GRBs to date. Our proposed observations will uncover additional short GRB afterglows to provide sub-arcsecond localization. *From Fong et al., in prep*.

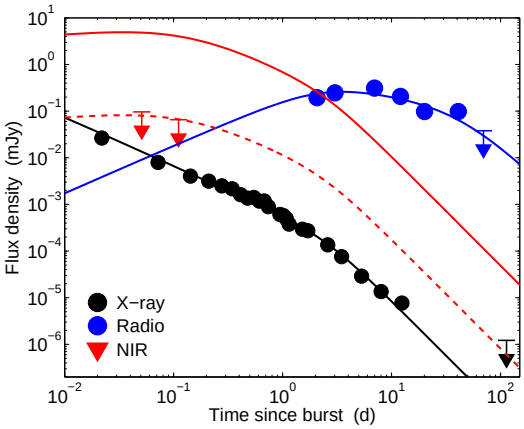

Figure 2: Broad-band afterglow light curves of the afterglow of the dark long GRB 110709B in X-ray (black circles), near-IR (red triangles) and radio (blue circles) bands. Triangles denote 3σ upper limits. The best-fit afterglow models are shown in each band (solid lines). The non-detection of the afterglow in the near-IR ($J \gtrsim 20$ AB mag) requires rest-frame extinction columns of $A_V \approx$ 4-10 mag (dotted line), highlighting the importance of near-IR observations in determining the extinction values at the sites of dark GRBs and the fraction of GRBs which reside in dusty environments. From [4].

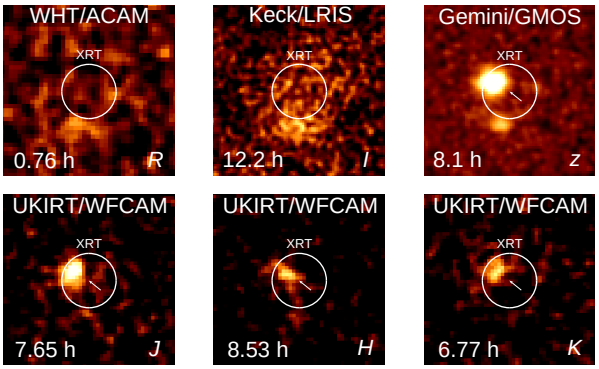

Figure 3: $RIzJHK$ imaging of the afterglow of GRB 120521C from UKIRT and other optical facilities within 9 hours after the burst. The emergence of the afterglow between I and z-bands, together with the UKIRT detections in JHK-bands enabled a photometric redshift determination of $z \approx 6.0$. Only six GRBs have been discovered at $z \gtrsim 6$, in part due to the paucity of sensitive near-IR instruments. Strikingly, four of these discoveries have involved UKIRT observations. We will take the same approach using a combination of LBT, MMT and UKIRT to discover and characterize additional events at $z \gtrsim 6$. From [3].

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

This proposal is for rapid TOO programs with the LBT, MMT and UKIRT for GRB afterglows.

1. Facility and instrument trigger criteria:

Given a burst that meets our science trigger criteria (see #2 below), here we outline under what conditions we will trigger various facilities, and the procedures we plan to follow. We emphasize that because the relevant instruments will not always be available, it is necessary to have TOO programs on multiple facilities with the same sky coverage so as not to miss out on a particularly exciting GRB.

- *LBT:* We will only trigger during Arizona non-LBTI runs. We will be in direct contact with the observer and will prepare observing blocks ahead of time. As we only request 0.5 night for the semester, we expect to interrupt LBT observing up to two separate times over the course of 2015B.
- *MMT:* We will only trigger MMTCam when f/5 instruments are mounted. We have experience with initiating rapid TOO observations through the scheduler (Nelson Caldwell) or through the operator directly if the burst occurs in the middle of the night.
- *UKIRT:* We will trigger at any time by creating MSBs when any of the instruments are mounted. We will be in contact with the Steward liasions to UKIRT (Peter Milne and Richard Green) and the scheduler directly.

2. Scientific trigger criteria:

Here we outline our science trigger criteria. We will trigger rapid TOO observations if:

- The GRB is reported as short (duration $\lesssim$2 sec) with a localization of $\lesssim$few arcmin.
- The GRB is reported as short and has a determined redshift (from our other programs or the community) of $z\lesssim 0.5$. We will then initiate a kilonova search on a ≈ 1 week timescale after the burst.
- The GRB is reported by the community as dark. This typically requires optical limits of $\gtrsim$22 mag reported $\lesssim$1 day after the burst. Optical/near-IR imaging will distinguish between a dust-obscured and high-redshift origin, as the detection of the burst in any optical band will immediately place the burst at $z\lesssim 6$.

3. Basic observing sequence:

Here, we outline our basic observing sequence. In practice, our observing plan will be subject to change in real-time based on instrument availability and nature of the burst.

- *Short GRBs:* 20-30 min of optical (and/or near-IR if available) imaging for afterglow identification, 20-30 min on next available night for confirmation of fading afterglow. If burst is identified by community to be at $z\lesssim 0.5$, initiate kilonova search and obtain two epochs of both optical and near-IR imaging, starting at $\approx$ 1-3 weeks after the burst.
- *Dark GRBs:* 20-30 min in each of the $riJK$-bands to obtain photometric redshift estimate and handle on the rest-frame extinction. If redshift estimate is $z\gtrsim 6$ (no detection in optical bands and the sudden appearance in the near-IR bands), trigger up to two additional imaging epochs in all near-IR bands (30 min each) to monitor afterglow.

4. Contingencies and Flexibilities: Since GRBs can occur at any time, we have virtually no constraints on the weather or moon brightness, but will evaluate the merits of using telescope time on a case-by-case basis. We will be as flexible as possible and work around the science of the scheduled observer, and will not interrupt if the scheduled observer needs continuous time for their science (e.g., planet transit). The PI and majority of the co-I's are very experienced in triggering TOO observations on facilities around the world and working around existing scheduling constraints. Our program is designed such that even one epoch of observations may be useful for a given burst if there are other factors (e.g., weather) which may impede the proposed observing sequence.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

For 2015A, we were awarded 0.2 nights (LBT) + 0.5 nights (MMT) + 2 nights (UKIRT) = 2.7 nights out of a requested 3.75 nights. Two months in to 2015A, we have not triggered any of these programs. For LBT, non-LBTI Arizona science runs have not occurred yet so we have not triggered. For UKIRT, the first AZ block with clear weather has just begun and no relevant bursts have occurred. *We were also given lower priority by the TAC, making rapid interrupt observations of higher-ranked programs difficult.* For MMT, f/5 instruments were mounted Feb 5-26, during which no relevant bursts occurred. We anticipate use of these programs later in the semester.

Based on the rates of past semesters, we anticipate that 3 short+4 dark GRBs will be observable with our programs in 2015B. Up to 1 of the short GRBs will result in a kilonova search. Across all facilities, we expect to spend an average on-source time per target of 2.5 hr. Folding in our basic observing sequence and including time for slewing and read-out, we request a total of 30 hr. Assuming 10 hr per night, our total request is thus **1.5 nights (UKIRT) + 1 night (MMT) + 0.5 night (LBT) = 3 nights**.

Since the PI's fellowship research largely depends on rapid TOO, we anticipate proposing for similar amounts of time over the next two years (the remainder of the PI's fellowship).

We are coordinating with partner institutions who will submit similar proposals through their TAC so we can conduct the observations beyond the Steward science runs. For LBT, we have included contributors at ASU (co-I's: Butler, Littlejohns). For MMT, we are coordinating with Harvard CfA (co-I: Berger). For UKIRT, we plan to expand and coordinate with partners in future semesters, after establishing collaborations at interested institutions.

As we do not know the targets in advance, it is possible that we will not use all of our allocated time, in which case it will go to the general Arizona allocation.

These TOO programs on optical/near-IR facilities in the North will provide a direct complement to our radio GRB program with the VLA (PI: Berger), X-ray programs with Chandra/XMM-Newton (PI: Fong) and UAO host galaxy programs (PI: Fong, proposed for 2015B). We plan to coordinate observations between these facilities to provide a comprehensive picture of every event.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

- ⋆ PI Fong was awarded 2 nights (LBT) + 1 night (Magellan) in 2014B for short GRB host galaxy follow-up. Two papers concentrated on single objects from this time are in preparation, and a third larger compilation publication will be released as the PI collects additional data in future semesters.
- ⋆ PI Fong triggered rapid TOO observations with Magellan (PI: Berger) and obtained UKIRT Director's Discretionary Time (PI: Fong) for the short GRB 150101B. These rapid TOO observations allowed for successful identification of the optical afterglow, and our group has the only detection of the afterglow. Due to the low redshift of this burst ($z = 0.134$), this burst has caused a splash in the community. PI Fong was lead author on five circulars to the GRB and supernova community for this burst alone. Planned publication date is April 2015.
- ⋆ Fong is a co-I on the AZTEC proposal (PI: Smith). Under this program, Fong and Milne triggered UKIRT observations of the long GRB 140916A at 2.7 hours after burst discovery, and placed a deep limit of J>21.9 AB mag on the near-IR afterglow, signifying either a dark GRB or high-redshift origin. This information was disseminated to the community within 12 hours of obtaining the observations and published in GCN 16826. Since a formal TOO program was not in place, we were unable to obtain follow-up observations to distinguish between the two scenarios.
- ⋆ We had a previously-approved GRB program (PI: Fan, "Probing the Epoch of Re-ionization with Gamma-ray Bursts") in conjunction with partners OSURC and INAF, concentrated on a single high-z GRB, which has never been triggered.
- ⋆ We had a previously-approved GRB program with MMT through Harvard (PI: Berger, "Identifying and Monitoring GRB Optical Afterglows with MMTCam") for 2014, actively used by Fong. This program enabled the discovery of the afterglow of the short GRB 140930B (published in GCN 16863) in September 2014.