OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

Development of 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 uncovered evidence for the narrow collimation of jets in some short GRBs, long GRBs heavily obscured by dust ("dark" GRBs), and long GRBs which originate at reionization redshifts of $z \gtrsim 6$. In addition, the recent 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 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 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) event rates, 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			2	bright	Jan-Jul	Jan-Jul	yes	yes
2	LBT	PF	LBC, MODS,LUCI			0.75	bright	Jan-Jul	Jan-Jul	yes	yes
3	MMT	f/5	MMTCam			1	bright	Jan-Jul	Jan-Jul	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 moon brightness.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ 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	TBD	TBD	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. Furthermore, the temporal and spectral behavior of the afterglow can lend invaluable insight into the GRB's jet geometry.

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 $z \gtrsim 6$. 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 an expansion upon the previously-approved program with the LBT (PI: Fan), and the initiation of such programs with MMT and UKIRT through Steward. All observations from these programs will be reduced, analyzed, and rapidly disseminated to the GRB community in real time via the GRB Coordinates Network Circulars. We note that we have directly complementary TOO programs in the radio (VLA, CARMA) and X-rays (XMM-Newton, Chandra) dedicated to GRB afterglows, and host galaxy follow-up programs on Steward facilities (proposed for 2015A, PI: Fong), which will provide stellar population properties. We are thus in a unique position to provide a comprehensive analysis of every event and intend for this set of programs to put Steward at the forefront in this exciting era of GRB discovery.

2. 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. Event rates and energy scales of short GRBs: Evidence for jet collimation in GRBs comes from temporal steepenings, or "jet breaks" in the afterglow light curves (Fig. 1) which occur at the time when the Lorentz factor, Γ, of the outflow is $\Gamma \approx 1/\theta_j$ (where θ_j is the jet angle). In general, a later jet break corresponds to a wider jet angle [5]. The distribution of jet collimation angles is crucial to constrain because of its direct effects on the true energy scale and event rate. For instance, a jet angle of 10° indicates that for every observed GRB, there are ~ 100 additional events with jets pointed away from Earth that escape detection. Similarly the true energy is lower by a factor of ~ 100 than the isotropic-equivalent value. An inference of the true short GRB rate will also aid our expectations for future coincident electromagnetic-gravitational wave detections. For short GRBs, the faintness of the afterglows limits effective ground-based observations to larger telescopes on timescales of $\lesssim$few days. For instance, the combination of small and large telescopes led to the detection of two jet breaks in short GRBs, translating to jet angles of $\approx$ 5-7° (Fig. 1). In a similar vein, here we propose to use MMT for rapid identification of the afterglow, and LBT to monitor the afterglow to $\gtrsim$1 day. As only two short GRBs have detected near-IR afterglows, mainly due to the paucity of sensitive near-IR facilities with TOO programs, the addition of UKIRT observations may uncover higher-redshift or dust-obscured events. We note that even if a jet break is not detected, the identification of an optical afterglow will be crucial in determining the host galaxy and redshift.

b. Electromagnetic counterparts to gravitational waves: Advanced LIGO, slated to begin operations in late 2015, will provide poor positions of $\gtrsim$100 sq. deg and will thus rely on a coincident electromagnetic signal to provide 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 recent 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 Advanced LIGO.

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 X-ray afterglow brightness that cannot be explained by a high-redshift origin (see next section), termed "dark" GRBs. A comparison of the optical/near-IR afterglow colors to the expected spectral slope for afterglows (flux $\propto \nu^{-0.5}$-ν^{-1}) 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, values of $A_V \approx$ 5-10 mag have been inferred from the lack of optical and near-IR afterglows to deep limits, combined with the detection of a radio afterglow. For example, through a radio through X-ray observational campaign of the afterglow of the dark GRB 110709B, we inferred $A_V \approx$ 4-10 mag, where limits of $JHK \gtrsim$19-21 mag provided the most stringent constraints on the extinction (Fig. 2; [6]). Thus, it is essential to use coordinated optical, near-IR, and radio observations to uncover additional bursts with moderate to significant extinction ($A_V \gtrsim$3 mag). These studies 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 re-ionization 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 in the JHK-bands led to a photometric redshift of $z \approx 6.0$ (Fig. 3; [4]). 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 is still small, 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] W. Fong et al. *ApJ* , 780:118, Jan 2014.
[4] T. Laskar et al. *ApJ* , 781:1, Jan 2014.
[5] R. Sari et al. *ApJ* , 519:L17–L20, Jul 1999.
[6] B. Zauderer et al. *ApJ* , 767:161, Apr 2013.

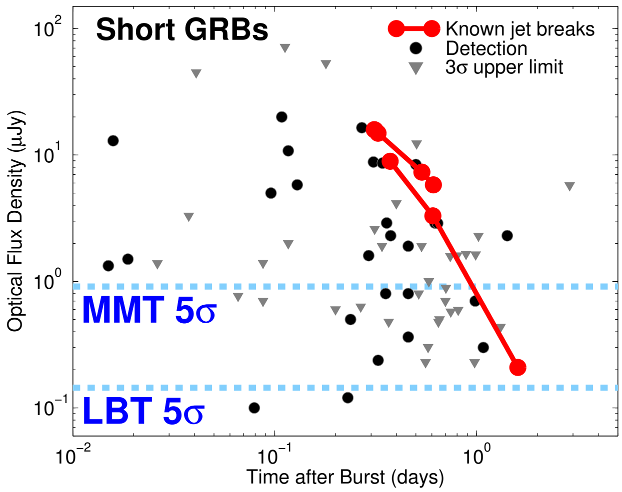

Figure 1: Compilation of optical afterglow detections (black circles) and 3σ upper limits (grey triangles) for 70 *Swift* short GRBs, including two jet break discoveries [3] (red). Jet breaks were not detected for other events due to inefficient searches. The limit for $\approx$ 30 min of r-band imaging with MMT/MMTCam and LBT/LBC are shown (blue dashed lines), demonstrating the need for both facilities in uncovering jet breaks. We plan to use these facilities to search for additional jet breaks in optical afterglows to provide constraints on the jet angles, and therefore true energy scale and event rate.

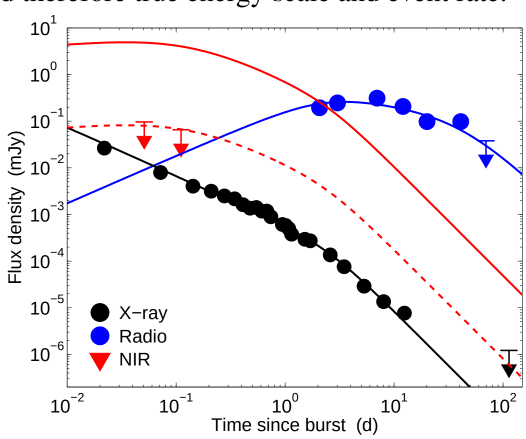

Figure 2: Broad-band afterglow light curves of the afterglow of the dark long GRB 110709B in X-ray (black circles), near-IR (red triangles) and radio (blue circles) bands. Triangles denote 3σ upper limits. The best-fit afterglow models are shown in each band (solid lines). The non-detection of the afterglow 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 [6].

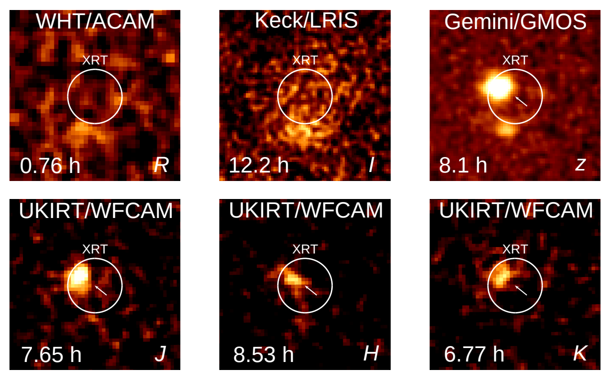

Figure 3: $RIzJHK$ imaging of the afterglow of GRB 120521C from UKIRT and other optical facilities within 9 hours after the burst. The emergence of the afterglow between I and z-bands, together with the UKIRT detections in JHK-bands enabled a photometric redshift determination of $z \approx 6.0$. Only 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 [4].

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)***

We aim to establish TOO programs with the LBT, MMT and UKIRT for GRB afterglows. The exact observing sequence will depend on the nature of the target and which, if any, facilities are available. We outline our trigger criteria and rough observing sequences below.

Short GRB jet breaks: If a burst is identified as short (duration < 2 sec) by *Swift*, we will trigger:

- *1st epoch:* Imaging for afterglow identification, as soon as possible after burst to reach 5σ depths of r$\sim$24 mag and J$\sim$21 mag. 30 min r-band imaging (MMT), 30 min J-band imaging (UKIRT).
- *2nd epoch:* Imaging for confirmation of fading afterglow, ideally on 2nd night after burst. 30 min r-band imaging (MMT), 30 min J-band imaging (UKIRT)
- *3rd epoch:* If afterglow is identified and detectable with LBT, trigger deep imaging for jet break search within ≈ 3 days of burst discovery to reach r$\sim$26 mag. 30 min r-band imaging (LBT).
- *n.b.* If bright optical afterglow is immediately identified in our 1st epoch, we will trigger 1 hr of spectroscopy if LBT/MODS/LUCI is available when the afterglow is $\lesssim$24 mag.

We anticipate that 3 short GRBs will be observable in 2015A. All 3 will require the 1st and 2nd epochs, and 2 will need the 3rd epoch. Up to 1 event will need LBT spectroscopy. Thus, we request 3 hr (MMT) + 3 hr (UKIRT) + 1.5 hr (LBT) for short GRB jet breaks. We note that even if LBT is unavailable, the identification of a short GRB afterglow is still essential in providing redshift and an association to a host galaxy.

Short GRB-kilonovae: The kilonova is predicted to be significantly redder than a typical GRB afterglow, necessitating relatively deep optical observations. We will only trigger observations of a low-redshift ($z\lesssim 0.5$) short GRB with an identified optical afterglow, and thus anticipate up to 1 trigger in 2015A. We will trigger 1 epoch at $\approx$ 7-10 days after the burst with 30 min r-band (LBT), 30 min J-band + 45 min K-band (UKIRT). If we detect a source, we will trigger an identical second epoch within $\approx$ 1 week after the first observation to confirm fading. This gives a total of 1 hr (LBT) + 2.5 hr (UKIRT) for kilonovae.

Dark and high-z GRBs: If *Swift* discovers a long GRB and optical limits of $\gtrsim$22 mag are reported at $\lesssim$1 day, we will trigger the following observations to distinguish between a dark or high-z origin:

- *1st epoch:* Optical/near-IR imaging to estimate a photometric redshift, triggered as soon as possible after the burst. 30 min in r- and i- bands (MMT), 30 min J-band, 45 min H- and K-bands (UKIRT).
- *2nd epoch:* If photometric redshift estimate is $z\gtrsim 6$, near-IR imaging to confirm fading (30 min J-band, 45 min H- and K-bands, UKIRT). Trigger 1.5 hr of spectroscopy if LBT/LUCI is available.

Based on rates of past dark and high-z GRBs, we anticipate requiring the 1st epoch up to 3 times and the 2nd epoch up to 1 time, for a total of 3 hr (MMT) + 8 hr (UKIRT) + 1.5 hr (LBT) for dark and high-z GRBs.

Taken together, the total on-source time requested is 6 hr (MMT) + 13.5 hr (UKIRT) + 4 hr (LBT). Including ample time for read-out, calibrations, and slew, and assuming 8-hr nights, we therefore request a total time allocation for 2015A of **1 night (MMT) + 2 nights (UKIRT) + 0.75 nights (LBT)**. As this is the inaugural "test" semester, we may not use all of this time, in which case it can go to the general Arizona allocation.

Contingencies and Flexibilities: We recognize we can only interrupt during Arizona runs (LBT/UKIRT), or when f/5 MMT instruments are on. So it's possible that a relevant GRB will occur and we cannot activate any of our programs. We will be as flexible as possible and work around the science of the scheduled observer. We will not interrupt if: scheduled observer needs continuous time for their science (e.g., planet transit), the telescope is in the wrong mode, or the wrong instrument is on the telescope and it will take $>$ 30 min to change. The PI and majority of the co-I's are experienced at triggering TOO observations and working around existing scheduling constraints. Similarly, we will adjust the observing plan in real time to account for "uncontrollables", such as weather, telescope issues, etc. For instance, if we obtain observations within 24 hr of burst discovery, and the second night is clouded out, we could still use observations taken at a later date to confirm fading and at least identify the afterglow. These classes of GRBs are rare enough that even the identification of an afterglow will be very useful.

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 request 1 night (MMT) + 0.75 nights (LBT) + 2 nights (UKIRT) = **3.75 nights** in total. This is the inaugural proposal for the project, and we anticipate that these will become long-standing programs, with similar amounts of time requested for future semesters. *Swift* is currently funded through 2016, so we at least anticipate extending this project over the next few years.

For LBT and MMT, 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), and we are actively talking with partners OSURC and INAF to organize a larger collaboration for 2015B and beyond. 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.

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 2015A). 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. These nights start in late October.
- ⋆ W. Fong is a co-I on the AZTEC proposal submitted for 2014B. 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, which was actually used by Fong to discover the afterglow of the short GRB 140930B (published in GCN 16863) the night before this proposal was due.