**EARLY AND DEEP FOLLOW-UP OF SWIFT GRBS WITH P60 AND THE SED MACHINE**

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## 1. Abstract

We propose to continue our successful program of rapid, deep, multi-filter follow-up of *Swift* gamma-ray bursts (GRBs) with the Palomar 60-inch telescope (P60). Our science goals are to: (A) Rapidly identify high-redshift and highly dust-obscured GRBs; (B) conduct multi-wavelength observations to identify reverse shocks and constrain the total energetics of GRBs; (C) build up large, high-quality, *unbiased* samples of optical light curves and host galaxies to enable demographic studies; (D) provide an automated, early-time spectroscopic capability to enable immediate redshift measurement and sensitive constraints on the color evolution of GRBs with the SED Machine.

## 2. Description of the Proposed Program

The P60 telescope is one of only a handful of 2-m class facilities worldwide equipped to robotically respond to GRBs. The additional depth provided relative to smaller facilities has emerged as a critical capability in an era where the typical *Swift* optical afterglow is only $R{\sim}19$ mag at ∼5–10 minutes after the GRB (Cenko et al., 2009; Akerlof & Swan, 2007), often precluding detection with smaller telescopes. This combination of rapid-response capability and depth not only enables more afterglow detections (we detect ∼80% of GRBs which P60 is able to observe within 20 minutes) but also provides an immediate handle on the afterglow properties: events not detected by P60 have been shown almost invariably to be either heavily dust-extinguished or, most excitingly, at $z > 5 - 6$ (Cenko et al., 2009; Perley et al., 2009).

The promptly available and rapidly disseminated (see below) results from P60 GRB observations enable a wide array of scientific investigations; we describe the primary science objectives of our team below. However, we wish to emphasize that by publicly (e.g., via GCN Circulars) reporting our results in a timely manner, we also enable the broader GRB community to more intelligently plan and execute their science programs at other (often larger-aperture) facilities.

*A) Heavily extinguished and high-$z$ GRBs*:

It has long been recognized that GRBs may serve as unique probes of the high-redshift universe, extending even into the epoch of reionization (e.g., Lamb & Reichart 2000). However, much of the difficultly in discovering high-redshift ($z > 6$) GRBs has come from the large number of false positives, especially from dust-extinguished events. The large aperture and red coverage of P60 are of considerable help in recognizing genuine high-$z$ bursts: the 80% detection efficiency from prompt P60 observations greatly reduces a significant contaminant to high-$z$ GRB searches (compared to, for example, the 50% detection rate from UVOT), enabling more efficient utilization of limited resources (NIR imaging and spectroscopy). P60 nondetections have played a central role in motivating NIR follow-up that directly led to the redshift measurements of two of three spectroscopically confirmed $z > 6$ events to date, (GRB 050904: Haislip et al. 2006; GRB 090423: Tanvir et al. 2009). Our group will continue to pursue access to NIR capabilities on large-aperture facilities in an attempt to utilize high-redshift events as probes of the epoch of reionization (e.g., Keck, Gemini); however, P60 non-detections will continue to be prime high-$z$ candidates for follow-up by the entire GRB community.

*B) Multiwavelength Modeling and Energetic GRBs*:

One of the remaining unresolved puzzles of the *Swift* era is the lack of achromatic jet breaks indicating collimation of the relativistic outflow (Kocevski & Butler, 2008; Racusin et al., 2009; Panaitescu, 2007). The resulting highly isotropic explosions have proven to be significantly more energetic than pre-*Swift* events, with several events exceeding a collimation-corrected energy release of $10^{52}$ erg (so-called "hyper-energetic" GRBs: Chandra et al. 2008; Cenko et al. 2006; Fig. 1b). Such a result is difficult to reconcile with the standard "collapsar" model for GRBs (Woosley, 1993). P60 will continue to provide detailed, multi-color light curves for *Swift* afterglows, in some cases extending out to weeks after the burst (Figure 1), to search for jet breaks and constrain event energetics. We also have a program at the VLA, enabling these events to be followed across the electromagnetic spectrum to better constrain the properties of mildly relativistic ejecta that are lacking from studies based only in the X-ray and optical bandpasses. Our approach has most recently been demonstrated in our observations and modeling of the bright *Swift*/*F*ermi GRB 130427A (Perley et al., 2013).

*C) Population Statistics for Swift GRBs*:

As *Swift* matures as a facility, attention has gradually shifted away from in-depth studies of individual events towards integrative studies of large populations of *Swift* bursts. However, the heterogeneous optical follow-up of GRBs presents a challenge: almost half of all *Swift* GRBs do not have reported optical afterglows, and those which do may be biased by selective observing or reporting and complicated by the different characteristics of different telescopes. P60 has been accumulating a sample of sensitive, multi-color, early-to-late time photometry of *Swift* bursts almost from the satellite launch through the present time. Since it is a robotic telescope, its automatically triggered events are fully unbiased by any human decision-making. We will continue our campaign to bolster this sample (currently standing at 62 events, 80% of which have detected afterglows, 65% with spectroscopic redshifts, and 100% with redshift upper limits) as well as to publish an updated catalog to the community within the next Cycle, building upon our previous release (Cenko et al., 2009; Perley et al., 2009).

*D) Rapid-Response Time-Resolved Spectroscopy*:

The SED Machine is a new P60 instrument with unique capabilities. While retaining the multi-color photometric follow-up capabilities of the previous P60 imaging camera (via its four-filter Rainbow Camera), the SED Machine also provides a completely new capability in the form of its 26×26" low-resolution IFU (Figure 2). The SED Machine can respond immediately to new GRBs to provide early photometric coverage and, once an X-ray position is acquired, the afterglow will be positioned onto the IFU for immediate spectroscopy. While the resolution $R{\sim}100$ is too low to provide traditional spectroscopic redshifts from metal lines, the SED Machine will be able to instantly recognize Lyman breaks (and DLAs) for GRBs at $2 < z < 6$, providing firm, precise redshift measurements without having to resort to observationally-intensive triggers on larger telescopes. In addition, by taking multiple exposures on the same source, the SED machine will provide a time-resolved window on optical color changes starting at very early times, providing simultaneous color measurements from $\lambda = 370 - 920\,\mathrm{nm}$ enabling the most detailed look yet at early-time color changes from both intrinsic GRB processes (evolution of the afterglow) and extrinsic ones (dust photodestruction).

## 3. Justification of Requested Observing Time, Feasibility, and Visibility

We expect to be able to respond to $\sim 6$ afterglows within an hour of the burst trigger with P60 over the course of Cycle 12 (based on numbers observed during previous cycles). Given P60 sensitivity limits ($R < 20.5$ mag in 60 s; $R < 23$ mag in 1 hr), all P60 identified afterglows will be suitable for follow-up optical spectroscopy on large facilities (e.g., Keck, Gemini) and, in many cases, late-time follow-up with P60 and with larger telescopes to monitor the light curve and build multi-wavelength SEDs.

Of the 6 GRBs with prompt P60 response, we expect $\sim 1 - 2$ will have no P60 detection and therefore be considered robust high-z or dark burst candidates. These events will be targeted for detailed studies in the NIR of the afterglow and/or host galaxy. At the other extreme, 1–2 afterglows per year will be sufficiently optically bright for long-term follow-up and energetics studies.

The SED Machine was commissioned in summer 2013 and is now available; during Cycle 12 it will alternate time on the telescope with the existing imaging camera. The SED Machine IFU reaches S/N>6 per resolution element down to $V \sim 20.5$ mag in 20 minutes, which should be sufficient to provide redshifts (or redshift upper limits) for at least ~50% of GRBs given the brightness distribution (2–4 events in Cycle 12 after installation). Any GRBs not detected at any wavelength on the IFU after 20 minutes (1–3 events) will be sent back to imaging with the Rainbow Camera and (if still undetected) pursued vigorously with other facilities as candidate dark bursts following the strategy outlined previously.

While the SED Machine instrument is meeting its performance goals, funding provided by this proposal will allow us to develop a *real-time, fully automated data reduction pipeline* for the IFU. With this in place, we can promptly notify the entire GRB community of the results from the SED machine so that they can schedule follow-up observations (e.g., NIR imaging/spectroscopy for high-$z$ candidates) appropriately.

We do not request any additional *Swift* observations for our program.

## 4. Justification of Duplication

We are proposing for funding to support ground-based observations of new GRBs, so there are no duplications.

### 5. Report on Previous Swift and Related Programs

We have previously been awarded funding from *Swift* for rapid optical follow-up with P60 in Cycles 1, 2, 4, and 5. The results of this work are best examined through the relevant publications (section 6) and GCN circulars. While P60 GRB operations have not been funded since 2009, we have made a concerted effort to continue our operations and rapidly announce results to the community: we have published 22 GCN circulars from P60 during the last 12 months; major recent results include a detailed study of the bright *Swift* GRB 130427A, which rapidly triggered and was extensively observed by P60 (Perley et al., 2013) as well as follow-up of the afterglow and supernovae associated with nearby GRBs 130702A (Singer et al., 2013; Toy et al., 2015) and 140606B (Singer et al., 2015; Cano et al., 2015). With the coming switch from the current camera to routine observations with the SED machine further support is critical for this effort to continue.

### 6. References

## References

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### 7. Budget Narrative

The current arrangement with Caltech Optical Observatories requires that users of P60 support operations through the science programs utilizing the telescope. We therefore request partial support for our expected fraction of P60 usage (10%, $20K) and an additional $10K for postdoc or student support to implement an updated triggering and rapid-reduction pipeline for SED machine follow-up of GRBs. This support ensures that P60 will be able to place *Swift* GRB followup as its highest scientific priority and to ensure a seamless transition in ToO operations between the current camera and the SED Machine.

Additionally, we request partial summer salary for co-I Harrison ($2K) and co-I Kulkarni ($2K), travel support for PI Perley and co-I Cenko ($3K), and associated research costs ($3K) including publication of an updated P60 afterglow catalog. These numbers are inclusive of overhead.

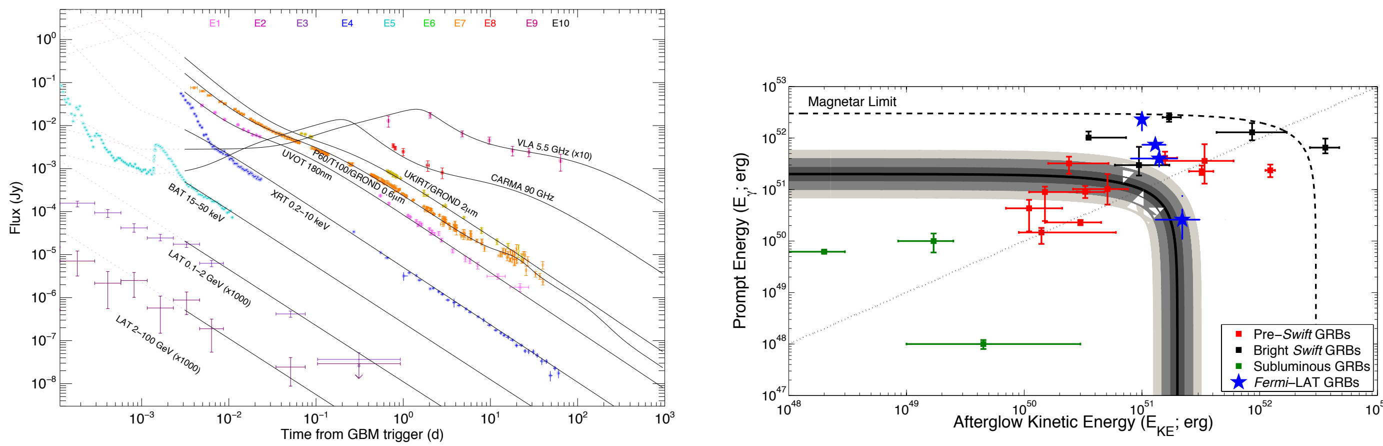


Figure 1: *(a) Left panel*: Multiwavelength observations and modeling of GRB 130427A (from Perley et al. 2013). Most of the $r$-band observations (as well as $g$,$r$, and $z$; not shown) were provided by P60. Radio observations were provided (in part) by our programs at VLA and CARMA. With this combined data set we were able to constrain the GRB properties (e.g., shockwave energy, microphysics) and environment (density structure) in detail and demonstrate the presence of a bright multiwavelength reverse shock. *(b) Right panel*: Two-dimensional relativistic energy release ($E_{\rm rel} \approx E_\gamma + E_{\rm KE}$) from GRBs. Cosmologically distant ($z > 0.5$) events from the pre-*Swift* era are shown in red. The logarithmic mean for these events, $\langle E_{\rm rel} \rangle = 2 \times 10^{51}$ erg, is indicated by the solid black line. Shaded regions correspond to $1\sigma$, $2\sigma$, and $3\sigma$ errors on this mean value. Nearby underluminous events (GRBs 980425, 031203, and 060218) are plotted in green. We have further identified a class of bright *Swift* and *Fermi* events that are over-luminous, with total energy release in excess of $10^{52}$ erg. Such hyper-energetic events pose a severe challenge to magnetar models.

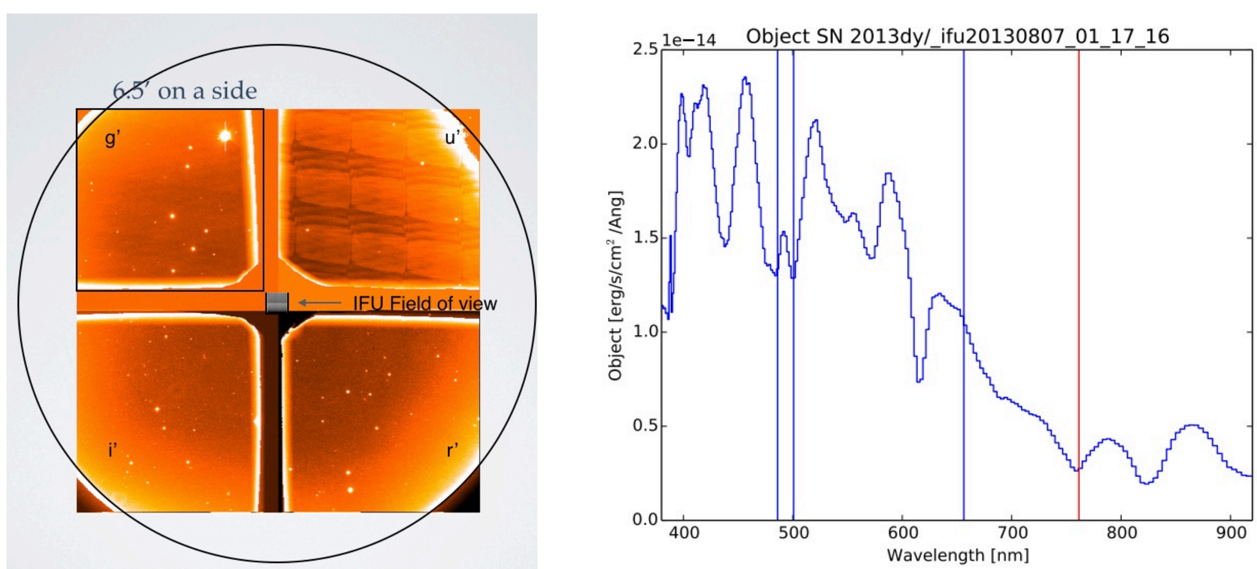


Figure 2: *(a) Left panel*: Focal plane layout of the SED machine, a combined imager (the four-filter Rainbow Camera) and IFU low-resolution spectrograph. BAT positions will be first be sent to the $r$-band quadrant of the Rainbow Camera for early light curve information, then (when the XRT position is distributed) the afterglow will be sent to the IFU to provide an immediate spectroscopic redshift as well as time-resolved $R \sim 100$ spectroscopy to constrain the afterglow's early color evolution. *(b) Right panel*: SED Machine spectrum of the type Ia supernova SN2013dy, obtained during commissioning in August 2013. The SED Machine IFU reaches S/N>6 per resolution element down to $V \sim 20.5$ mag in 20 minutes, which should be sufficient to provide redshifts (or redshift upper limits) for the majority of *Swift* GRBs.