# OPTICALLY IDENTIFIED RELATIVISTIC EXPLOSIONS: DIRTY FIREBALLS AND ORPHAN AFTERGLOWS

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## 1. Scientific Objectives

*1.1 Science Goals:* Two central tenets of our standard model of long-duration gamma-ray bursts (GRBs) hold that these explosions are ultrarelativistic (initial Lorentz factor $\Gamma_0 \gtrsim 100$) and highly collimated (biconical jets with half-opening angle $\theta \approx 1$–$10°$). The former is invoked to explain the so-called "compactness" problem: absent this ultrarelativistic expansion, the ejecta would be optically thick to pair production at typical peak spectral energies of a few hundred keV, whereas the prompt emission is observed to be nonthermal. On the other hand, a high degree of collimation is required for basic energy conservation: the isotropic energy release can in some cases exceed $10^{54}$ erg, comparable to the rest-mass energy of their massive-star progenitors.

In order to accelerate material to these velocities, the amount of mass entrained in the outgoing jet must be very small ($M_{\rm ej} \approx 10^{-5}\,{\rm M}_{\odot}$); this is referred to as the "baryon loading" of the jet. Most *observed* GRB prompt spectra, with peak spectral energies of a few hundred keV, therefore indicate very "clean" outflows (i.e., low mass of entrained baryons; [1]). But there is growing evidence that the intrinsic population of long GRBs is dominated by bursts with peak energies below the traditional $\gamma$-ray bandpass (e.g., [2, 3]). Could these lower $E_{\rm pk}$, fainter outbursts (e.g., X-ray flashes; [4]) result from an outflow with more entrained mass (i.e., a "dirty" fireball; [5, 6])? Or can other properties, such as viewing angle [7] or the nature of the remnant [8] account for these softer events?

Separately, the high degree of collimation requires that most ($f_b \equiv (1 - \cos\langle\theta\rangle)^{-1} \approx 100$; [9]) GRBs are in fact beamed away from us on Earth. The afterglows of these off-axis bursts become visible at late times ($t \gg \Delta t_{\rm GRB}$) when the outflow slows down and illuminates an increasing fraction of the sky [10, 11]. Yet despite concerted efforts at uncovering such orphan afterglows in the X-ray [12, 13, 14], optical [15, 16, 17], and radio [18] bandpasses, no *bona fide* off-axis candidate has been identified thus far.

All of these issues can be addressed by sensitive, wide-field surveys that target relativistic explosions independent of any high-energy trigger. To this end, our objective here is to *discover optical transients resulting from relativistic outflows, independent of any associated high-energy emission.* This includes both dirty fireballs and orphan (i.e., off-axis) afterglows. With its large field-of-view and **demonstrated** rapid-response software pipeline (e.g., [19]), ZTF could represent an order-of-magnitude improvement in capability to detect fast optical transients. For example, models from [20] suggest that ZTF will be capable of detecting $\sim 20$ orphan afterglows per year (to reiterate, no viable off-axis afterglows have yet been identified).

*1.2 Figure of Merit:* As of the time of writing, only five *bona fide* relativistic outflows have been discovered independently of a high-energy trigger. Two of these (iPTF14yb [19] and ATLAS17aeu) turned out to be regular GRB afterglows (i.e., on-axis events with high-energy emission; it is just that the GRB was identified after the optical transient discovery). Two "relativistic supernovae" (SN2009bb [21] and SN2012ap [22]) were identified from radio follow-up of (optically discovered) SNe Ic. The one remaining source, PTF11agg [23], remains of ambiguous origin (possible dirty fireball). Given the rarity of these events, our figure of merit is simply *the number of relativistic outbursts discovered directly by ZTF.* To be clear, inherent in this definition is that these sources must be identified, promptly followed up, and distinguished from foreground and background contaminants (e.g., flaring low-mass stars).

*1.3 Database Queries:* Our sources of interest will behave largely like GRB afterglows: bright but rapidly fading isolated point sources. Thus our searches through the transient stream will require suitably fast evolution (e.g., $\Delta{\rm mag} > 0.5$ in $\Delta t < 1$hr, at some reasonable threshold). Depending on the fidelity of the data stream (i.e., fraction of artifacts), these may require some level of human scanning. However, we note that because they are isolated point sources, these are some of the easiest transient candidates to identify (aside from their fast fading).

To filter out false positives (flaring low-mass stars and CV outbursts), we will also cross-correlate transient detections on the deepest and reddest imaging available for the transient location. This may include PS1, 2MASS, WFCAM, WISE, etc.

## 2. Proposed Observations

*2.1 Requested Observational Strategy:* Assuming 4 hours per night is available for collaboration time, we request 6 observations (every 40 minutes) per night of $2500\,{\rm deg}^2$. The most critical aspect of our request is that **these same fields be revisited every night.** The filter sequence for these observations is not critical – **as long as at least 4**

**observations are obtained in one filter** (e.g., gRRRRg, gRgRRRR, ggRRRR, etc.). We have a preference that the filter observed four times be $R$-band, as GRB SEDs are modestly red, the most common contaminants (M dwarf flares, CV outbursts) are quite blue, and redder filters decrease the impact of extinction (either from the Milky Way or the host galaxy). However $g$-band would also be acceptable. The fields could be selected to suit other science cases (nearby galaxies, or even pushing down to modest Galactic latitudes would be acceptable). Our request is to implement this strategy for the bulk of the first year of ZTF operations (modulo small well-defined projects that clearly cannot be achieved with this strategy). This is clearly distinct from the MSIP program and would (we believe) address many other science goals (e.g., young supernovae).

We estimate the yield of fast optical transients using the rates derived from our study of iPTF14yb [19]: $\approx 600\,\mathrm{yr}^{-1}$. Including a 40% weather less, our proposed observing strategy implies a discovery rate of $\approx 20\,\mathrm{yr}^{-1}$, or $\approx 2\,\mathrm{month}^{-1}$.

We have performed simulations for four different observational strategies: 4 observations per field per night (RRRR), 6 observations per field per night (RRggRR), and 8 observations per field per night (RRggggRR). In each case we assumed an iPTF14yb-like light curve and the all-sky rate quoted above. While the 4X strategy resulted in the largest number of fast transient detections, the vast majority (70%) were only detected twice. This would make identification more difficult. The 6X strategy yielded 20% fewer detections, but more than half were detected in at least three images, and all had multiple detections in the same filter. The 8x strategy further reduced the number of detections without greatly increasing the fraction detected at least three times. Hence our preferred strategy involves 6 observations per night.

*2.2 Sensitivity to Variations:* As discussed above, the most important aspect of our requested observing strategy is **to maintain a regular (1 day) cadence** on the fields of interest. Strict non-detection limits are necessary for our proposed science. We also require multiple observations of each field per night – at least 4 observations in a single filter are necessary to efficiently identify these sources.

Aside from these “requirements”, our figure of merit scales linearly with sky area covered. As discussed above, it is relatively insensitive to filter choice, field location (modulo foreground extinction), or the exact number and spacing of epochs per night.

*2.3 Suitable Observing Periods:* The proposed project is suitable for any time of year, though if this were only to be executed for some fraction of a year, we would prefer to avoid winter (when it is very difficult to maintain a daily cadence).

**3. Supporting Observations** Above we estimated our relativistic transient discovery rate of $2\,\mathrm{month}^{-1}$. In order to plan for the required follow-up, we must also estimate the rate of false positives. [24] find that fast foreground contaminants discovered by the Pan-STARRS1 Medium Deep Survey could be filtered out based on either proper motion (i.e., asteroids) or the presence of a faint, red counterpart in reference imaging, suggesting that the rate of false positives will be quite low. Our experience with iPTF suggests a more complicated story (i.e., more false positives). For planning purposes, we assume a false positive rate that is $3\times$ the *bona fide* relativistic transient rate, i.e., 8 candidate events per month requiring follow-up of some sort.

*3.1 Photometric Follow-Up:* Observing the late-time photometric evolution of relativistic transients is important to constrain the geometry of the event, so we plan for observations when the spectroscopically confirmed candidates have faded below ZTF sensitivity. This will require access to photometers on medium to large aperture facilities – however, with only two discoveries per month and several hours of follow-up required (per source), the total requirement is only $\approx 5\,\mathrm{hr}$ of imaging. We will use access to proprietary facilities (P200, Keck, DCT, APO) to meet this need.

*3.2 Additional Usage of Other Facilities:* Given the rarity of these events, searching on other facilities is not a feasible approach.

*3.3 Spectral Follow-Up:* Since the sources fade quickly, we require rapid-response ToO spectra in order to classify these transients. However, given the relatively small number of candidates requiring classification (estimated above at 8 per month), with 1 hour per source, the total spectroscopic follow-up required is only 8 hours per month. This could in principle we accomplished by the SEDM, as the spectra of flaring low-mass stars and CV outbursts should be easily distinguishable from GRB afterglows. However, for studies of the host galaxy environment, we require high signal-to-noise ratios and increased spectral resolution. We have access to spectroscopic follow-up at Palomar (Kulkarni), Keck (Kulkarni), DCT (Cenko), and APO (Bellm) that we will utilize for this purpose. While we will likely only need a few hours per month for this purpose, having facilities distributed around the globe will be a critical hedge against e.g., weather.

*3.4 External Resources:* Multi-wavelength follow-up is critical for these sources, in order to constrain properties of both the outflow (geometry, energetics) and the environment (density, density profile). Team Member Cenko is the Deputy Project Scientist for the *Swift* mission and will ensure prompt X-ray follow-up of these discoveries. We will aggressively compete for radio follow-up with the VLA and may leverage external collaborations for AMI access in order to obtain the requisite multi-wavelength coverage.

**4. Required Expertise**

*4.1 Expertise / External Collaborators:* Our team has all the requisite expertise in order to conduct this project. We have published discovery papers from iPTF on the first dirty fireball candidate (PTF11agg [23]) and the first optically discovered GRB afterglow (iPTF14yb [19]). All reduction, and analysis can be handled by team members from ZTF partner institutions. However we may include a few external collaborators (Horesh, Corsi, Perley) for their scientific expertise and additional resources they can bring to bear.

*4.2 Required Tools:* We do not anticipate the need for any particularly unique tools for this project, aside from standard access to the marshal, data reduction packages, etc.

**5. Manpower and Time**

*5.1 Team Members:* Team members include Brad Cenko (NASA/GSFC), Shri Kulkarni (Caltech), Eric Bellm (UW), Anna Ho (Caltech), and Ginny Cunningham (UMd). Each discovery will be published in a single object paper, and after a year a paper on rates will be put together.

*5.2 Thesis Project:* Fast extragalactic transients will make up a substantial component of the graduate thesis projects of students Anna Ho (Caltech) and Ginny Cunningham (UMd). These students will be supervised by Team Members Kulkarni and Cenko, respectively.

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