SEDM Proposal:
The First Optically Selected Population of Relativistic Afterglows

Part 1: Summary (1 paragraph)

With ZTF, we have the cadence and areal coverage to assemble the first *optically selected* population of afterglow emission from relativistic stellar explosions. This is a formidable technical challenge due to the fog of false positives, primarily stellar flares. Our goal is to use SEDM to perform immediate (intra-night) discrimination of afterglow emission, which should obey a synchrotron spectrum ($\nu^{-0.7}$). By contrast, stellar flares should obey the Rayleigh-Jeans tail of a blackbody spectrum (ν^{+2}). This rapid discrimination is a key filtering step for our approved ToO programs on radio telescopes, which are necessary for confirming the presence of a relativistic outflow.

Part II: Team Members / Resources

- *PI/Point of Contact:* Anna Ho (Caltech), `ah@astro.caltech.edu`
- *Co-Is:* Shri Kulkarni (Caltech), Dan Perley (LJMU), Adam Miller (Northwestern), Steve Schulze (Weizmann), Igor Andreoni (Caltech), Eric Bellm (UW), Brad Cenko (NASA Goddard/JSI), David Kaplan (UW-Madison), Zach Golkhou (UW)

- *Science Working Group:* Physics of supernovae and relativistic explosions

For Semester 2019A, we have the following accepted proposals:

- LCO (PI Adam Miller): 25 hours for rapid follow-up of young, relativistic explosions and Type Ia supernovae
- APO (PI Eric Bellm): Two TOO triggers for fast transients, both spectroscopy and imaging
- P200 (PI Shri Kulkarni): 15 nights for classification of ZTF transients. Relevant to this proposal is that this program includes host redshifts for bright ($r \lesssim 20.5$) galaxies.
- Keck (PI Shri Kulkarni): 5 nights for follow-up of ZTF transients. Relevant to this proposal is that this program includes host redshifts for faint ($r > 20.5$) galaxies.
- ToO P200 and Keck (PI Scott Adams): 4 triggers for candidate relativistic stellar explosions
- Liverpool Telescope (PI Dan Perley): 10.5 hours total for fast transients, intended for 5–10 events over the semester. Program includes SPRAT spectroscopy over 5 epochs (typically, nightly over the first 5 days) plus complementary imaging (35 minutes per epoch including overheads), plus an additional 12 imaging epochs of 15 minutes each (on average) to follow the transient to late times in several bands.
- Very Large Array (PI Dan Perley): 46 hours at Priority A to search for radio afterglow emission from candidate relativistic explosions
- Swift (PI Dan Perley, joint with VLA proposal): 10 ksec to search for X-ray afterglow emission from candidate relativistic explosions

Part III: Science Objectives (1 page)

In $\sim 0.1\%$ of core-collapse supernovae, a collimated relativistic outflow ("jet") is launched and drills through the stellar envelope. Viewed on-axis, the jet produces a long-duration gamma-ray burst (GRB) lasting several seconds, and its collision with the circumstellar medium (CSM) produces an "afterglow" that radiates across the EM spectrum for days to months.

A major focus of scientific investigation over the past 20 years has been to understand the diversity in successful jets, as well as the connections between "extreme" jet-associated SNe and ordinary SNe without them. For example, GRB jets must accelerate only a tiny fraction of their mass in order to achieve hyper-relativistic ($\Gamma > 100$) speeds and produce observable gamma-ray emission: is this fractional mass fundamental, or the tip of the iceberg of jet properties? What fraction of SNe launch jets in the first place? How accurate is our model of jet collimation and beaming in GRBs?

Progress has been hampered by selection effects: out of the thousands of jets identified, nearly all were discovered via the GRB. However, if a jet has too much entrained mass to accelerate ejecta to ultra-relativistic velocities, gamma-ray emission will be stifled due to pair production [1]. If a jet is directed away from Earth ("off-axis") then relativistic beaming will preclude a GRB [2]. These variations on the GRB model have been predicted to exist (off-axis afterglows must exist, if our model of beaming is correct!) but never definitively found. **ZTF has the areal coverage and cadence to discover optical afterglow emission independently of a GRB trigger [3; 4], enabling us to construct the first optically selected population of relativistic outflows.**

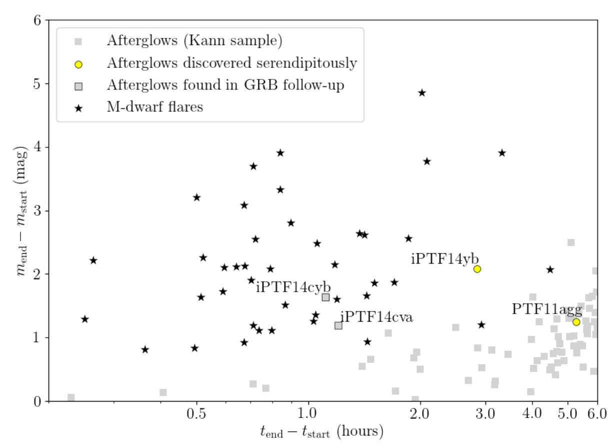

Figure 1. The $(\Delta t, \Delta m)$ for the 41 candidates from PTF/iPTF that show significant (5-σ) intra-night fading (asteroids and artifacts of bad subtractions have been removed). The grey unlabeled points are a sample of GRB afterglows from [8]. In our sample, filtering out M-dwarf flares exclusively identifies PTF11agg and iPTF14yb, afterglows discovered serendipitously by PTF/iPTF [7; 3], as well as two afterglows found in follow-up to Fermi GRB triggers.

Identifying afterglow emission without a GRB trigger is challenging because of the short duration (fade from $r \sim 18$ mag to below-threshold overnight) and rarity compared to SNe [5]. From our systematic analysis of rapidly fading sources in PTF and iPTF [4], we found that the dominant false positive was stellar flares (see Figure). These can be easily mitigated using colors: the flares themselves are thermal (blue; ν^2), whereas afterglows have synchrotron (red; $\nu^{-0.7}$) spectra. Furthermore, many host stars are bright enough to have red quiescent counterparts in Pan-STARRS, whereas a typical on-axis afterglow would be hostless (high-z), and any detectable off-axis afterglow would have a detectable host galaxy [6].

Confirmation that a rapidly fading source is a relativistic outflow requires (1) a host galaxy redshift that establishes a high luminosity $M < -21$, and (2) the detection of an X-ray and/or radio counterpart. To this end, we have approved programs on optical, radio, and X-ray facilities. The SEDM, with its flexiblity in triggering urgent intra-night observations, will optimize our use of these follow-up programs by enabling us to promptly filter out stellar flares based on their colors.

Part IV: Past Usage (1 page)

This is our first time submitting an SEDM proposal for this science case.

Part V: Observing Details (1 page)

Triggering Criteria:

The primary discovery channel will be the partnership survey, due to its high cadence. Following our experience vetting afterglows in PTF/iPTF [4] as well as in the first 9 months of ZTF, we will trigger SEDM on transients that satisfy the following criteria:

- Significant (5-σ) fading between detections
- No history of detections at that position
- No star at that position (based on the ZTF star/galaxy machine learning classifier)
- No known AGN or variable star at that position

From our archival search of iPTF data [4] we found that a conservative estimate is **three classical on-axis afterglows in eight months**, with an overall false positive rate of 20:1. Many of these false positives will be filtered out via the presence of a red stellar counterpart in Pan-STARRS. Including only the faint hosts (< 20 mag), we estimate a false positive rate of 6:1. Therefore, **we request a total of 20 imaging triggers.**

Trigger Method:

GROWTH Marshal programs: Fast Transients, Rapidly Evolving Transients

Observing Sequence / Total Time Request:

We estimate that the transient will be 20th mag by the time of observation, well within the limit of the P60 rainbow camera. For a robust color measurement, and confirmation of a power-law spectrum, we request observations in three filters: g, r, and i. Thus, **we request a total of 20 triggers, each with three images. For 180 s per image, assuming an overhead of 40 s per image (the longest read-out time in [9]), our request amounts to 13.2 ks, or 8.25 hours.**

Part VI: Publication Plans

This program is a major component of PI Anna Ho's thesis. The planned timeline is as follows:

- A paper submitted in late 2019, presenting the collection of optically selected afterglows, and making comparisons to the well-studied GRB-selected population.
- (In the event of no discoveries of orphan afterglows) A paper submitted in late 2020, presenting constraints on the properties and rates of orphan afterglows given their non-detection.
- If any dirty fireball or orphan afterglow is discovered, it will be its own (rapid turnaround!) single-object paper.

REFERENCES

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