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Measurement of the Optical-IR Spectral Shape of Prompt Gamma-Ray Burst Emission: A Timely Call to Action for Gamma-Ray Burst Science

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Principal Author:

Name: Bruce Grossan
Institution: UC Berkeley Space Sciences Laboratory
Email: Bruce_Grossan@lbl.gov
Phone: 510.735.8806

Co-authors: (names and institutions)

Pawan Kumar, Dept. of Astronomy, University of Texas at Austin; Kevin Hurley, UC Berkeley; Bing Zhang, Dept. of Physics and Astronomy, University of Nevada, Las Vegas

Abstract (optional):

There is still no consensus on the emission mechanism of any type of gamma-ray burst (GRB). This is because a given gamma-band spectrum can come from different mechanisms. Measurement of the prompt optical-IR (OIR) spectral shape (POSS) breaks this degeneracy, however. There are also no direct measurements of the physical conditions in the relativistic jets where bursts originate. If the synchrotron self-absorption frequency, ν_a, expected in the OIR region, can be measured, the radius of emission, the electron Lorentz factor, and the B field can be determined. Solving the 50+ year mystery of the emission mechanism is critical for understanding the light we observe from GRBs, and therefore the general problem of the physics of the jet.

Although single band prompt optical fluxes have been measured, no POSS measurement has been made, because telescopes with multi-channel cameras cannot point within the $\lesssim$ 10 s required. For a good chance of measuring ν_a, near-IR (NIR)-optical coverage is also required. NIR measurements require ~ 2-m aperture ground-based telescopes, in turn requiring major engineering efforts for fast pointing. Space telescopes co-located with a gamma instrument have orders of magnitude lower NIR background, always point near the GRB, and unaffected by weather, yield a much higher detection rate. A ~30 cm space telescope with ≥ 4 OIR imaging channels would measure POSS from most GRBs. Technological advances make fast-pointing feasible. Sub-second time

resolution data from electron multiplied CCDs will allow cross-correlation of optical and gamma-band data, allowing separation of multi-component spectra. Any GRB mission with $\lesssim$ several arc min localization could then do this science if a POSS instrument were added; no planned missions have this capability, however, even those with OIR telescopes. Trading away the fast-slew and simultaneous multi-channel cameras required, for, e.g., greater sensitivity, results in the loss of fundamental emission mechanism science for only incremental science gains elsewhere. We also note additional capabilities enabled by a POSS-capable instrument, including dust evaporation identification and photo-z.

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1 Introduction

1.1 GRB Emission Mechanism Science is Stuck

Gamma-ray Bursts (GRBs) are a compelling field of study. They are the most energetic explosions in the universe. Near peak, distant GRBs can be far brighter in the optical than any other object at extragalactic distances, suggesting they may be used as "bright backlights" allowing the study of the intervening universe through absorption spectroscopy. GRBs are bright enough to be detectable with current instruments to $z > 10$ ([1]) if present. To use GRBs for precise measurements, however, we need to understand them better.

For the last half-century, virtually every type of instrument has been used to study these events and their aftermath. Hundreds of GRB spectra have been measured from soft-X through ~ GeV energies, and even gravitational waves have been measured for one GRB. However, there is still no consensus on the emission mechanism of any class of GRB, and though they are thought to originate from a relativistic jet, there are only very limited and indirect measurements of the basic physical conditions in these jets. The featureless power laws observed in the ~ 20 keV up to GeV bands, even for any proposed sub-group of GRBs, cannot be attributed to a unique emission mechanism. **Where will new information come from to improve our understanding of this mechanism?**

1.2 The GRB Prompt Optical-IR Spectral Shape (POSS)

A new approach is possible with time resolved, multi-channel optical-IR (OIR) observations to measure the prompt OIR spectral shape (POSS) of GRBs. The majority of OIR data on GRBs are of the afterglows (AGs), not the actual burst, or "prompt" emission. AG emission, the interaction of the GRB with the interstellar medium (ISM), is dependent on the ISM density profile, and carries only indirect information about the burst.

Most models invoke some kind of synchrotron mechanism to produce the bright prompt burst in γ-ray bands. Shen & Zhang, 2009 ([2]), showed that for a single synchrotron component there are four cases of observed emission, depending on the relative values of the synchrotron self-absorption frequency, ν_a, the frequency given by the minimum electron injection energy/h, and the frequency of the center of the optical band. *For all four cases, the X-γ bands have identical spectra, but different POSS.* For a single-component dominated spectrum then, POSS can identify the mechanism (or case), and breaks the degeneracy of the featureless γ band power laws. In addition, measurement of ν_a encodes rich information about the physical processes in the jet: the emission radius, the electron thermal Lorentz factor $\mathbf{\Gamma}$, and the B field in the emission region as well. (In the case of photospheric emission, it gives $\mathbf{\Gamma}$.) Many GRB are single-component dominated[2], however, below we discuss how to separate multiple components. Measuring ν_a and determining the emission mechanism of GRBs will be the great leap forward theorists need to make new, far more detailed models, of physical processes in the GRB jet. Progress here should also apply to the general class of relativistic astrophysical jets as well.

Unfortunately, we have no measurements of POSS. Perhaps the best measured optical prompt data is that for 080319b. While dozens of channels were measured in the γ bands, only one unfiltered CCD measurement was given in the optical. Such data give us no information on the spectral *shape* in the optical, however, underscoring our ignorance of GRB POSS compared to γ-band spectra. The physical parameters discussed above remain a mystery. Such measurements have never been made because sensitive instruments cannot point at GRBs before prompt emission ceases (Long GRBs have a typical duration ~60 s, depending on instrument[3,4,5]). The Neil Gehrels *Swift* UVOT is the origin of most early optical data, after location of the bursts with the Burst Alert Telescope (BAT). *Swift*-UVOT has a typical response time of ~ 100 s, far too long. In addition, with a filter wheel and a single detector array, it can only measure colors of steady sources, not rapidly variable GRBs. Ground-based telescopes can follow up on BAT internet position alerts, which arrive as early as a few sec. after trigger. Most ground-based telescopes take more than several minutes to point, however, far too slow to study prompt emission. Specialized instruments, such as ROTSE-III[6], and Master-net[7], have measured prompt emission, but only in one, usually unfiltered, CCD channel. These instruments also cannot measure POSS.

1.3 Missed Opportunities

Though the theory community explicitly (e.g., in [2]) recognizes the importance of measuring POSS, this is not reflected in planned missions. No likely proposed GRB mission has the OIR capability for POSS: TAP, SVOM, and THESEUS have OIR instruments, but suitable only for AG observations. SVOM includes ground-based telescopes (GWAC), but these are only single channel, and cannot measure POSS or ν_a. We therefore direct this paper to scientific decision makers at space agencies, and GRB instrument teams. We issue an urgent call to action for any mission that can localize GRBs to ~ arc min, to strongly consider the enormous scientific gain of adding a POSS-capable OIR instrument, even if the costs are significant.

2 A Generic Space Instrument

This paper promotes no specific mission or hardware design, but we describe a "strawman" instrument for POSS measurement, primarily intended as an "add-on" to a γ-ray instrument.

Gamma-Band Instrument: Smaller than BAT is OK. GRBs are first discovered and roughly located by a γ-ray sensitive instrument, because GRBs are extremely bright compared to the time-averaged γ-ray sky, and because γ-ray instruments commonly cover a large fraction of the sky, necessary for these ~ once/day/sky events. Any instrument that provides ~ few dozen localizations/year (Section 3), with 90% probability radius$\lesssim$ 8', would be adequate. The BAT (shadow mask camera, CZT array ~5000 cm^2, 90 GRB/year **σ** ~ 2'-3') is far better than required. A significantly smaller, less sensitive, γ band instrument would suffice, e.g. ~ 1000 cm^2([8]).

OIR Telescope In order to record the majority of a burst, the POSS instrument must point and track in much less than the typical GRB duration; we require ≤ 10 s for these ~60 s bursts. Most of the field of view (FOV) of the γ instrument, ~ 1.5 Sr for BAT, must be covered. Ultra-wide FOV optical instruments (e.g. Pi of the Sky[9]) might cover such a field, but are thus far not sensitive, and not amenable to multiple channels. We choose a more typical telescope on a fast mount. On a large satellite, the torque caused by slewing a small telescope would not be a problem; on a small satellite, torques could be easily mitigated, e.g. by a counter-rotating wheel parallel to each axis.

The Multi-Channel Imager We need to measure power law slopes and turnover frequencies, not emission lines, so a multi-channel imager is sufficient. Here, the telescope beam is split into separate bands by means of dichroics, and simultaneously delivered to different cameras, like in the GROND instrument[10]

IR-optical Coverage We have limited information regarding the value of ν_a. Many theoretical estimates suggest that ν_a is likely to be "near" optical frequencies (e.g. [2], [11]). Without any better *a priori* restriction on ν_a, we therefore argue for as wide a spectral range as practical. Wider separation between filters also generally gives more accurate slopes. Sloan b'-i' filters span from ~380-880 nm, a factor of 2.7 in frequency. Extending this to Ks, at 2330 nm in the near-IR (NIR) gives a factor of 7.1 in

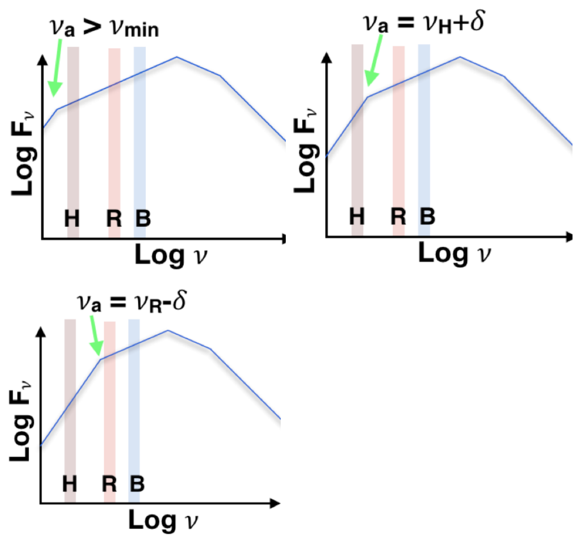

Figure 1 Sychrotron emission with ν_a below the instrument band (case IV), ν_a just above the first filter frequency, and finally, ν_a just below the second filter frequency (in-between cases III & IV). Three filters give two slopes; different slopes indicate the presence of ν_a between filters. Here, the lowest frequency log slope=2, and the next higher frequency slope=+1/3; measurement of either infers the other, giving the value of ν_a (at the intersection of the power laws). For cases I & II (not shown), the low frequency log slope=5/2, the next slope is that measured in X-rays, and a similar solution is obtained.). Note that the gamma ray region is identical in all cases.

frequency, much greater coverage. Additionally, the *majority* of GRBs have at least moderate extinction[20], so a NIR channel would detect ~ 1.6 times more bursts[8].

Justification of a Space Instrument We measured the time for a small (70 cm) aperture commercial telescope to slew 180 deg. in azimuth and track to be < 8 s[12]. The same manufacturer, and others, indicated that ≥ 1-m telescopes are *several times* slower. NIR observations from the ground, however, generally require ≥ 2 m apertures for good sensitivity for extragalactic targets, especially at exposures << 60 s GRB duration, *making POSS inherently problematic from the ground*. NIR backgrounds in space are *thousands* of times weaker, however, so much smaller space-based telescopes will suffice. In [8] it was shown that essentially all UVOT GRBs detected at 120 s after trigger (likely fainter than during prompt emission) would be detected in B–K_s bands with a 30 cm space telescope. It is straightforward to design such a telescope to point anywhere in a ~ 1.5 Sr FOV in < 10 s. We therefore baseline a 30 cm space-based telescope.

A second argument for a space platform is the ground-based detection rate: Of the ~ 90 Swift GRBs/yr, ROTSE-III reported ~ 3 prompt detections/yr[8]. Clouds, daylight, and the moving FOV of BAT make for a very low detection rate. This might be increased by a factor of a few with more sites. However, custom-built fast 2+ m telescopes plus cameras are most likely a few times $10M projects, > $30M-$40M for 3-4 sites producing ~ 10-15 detections/yr. (including the NIR factor 1.6). This cost is not far off the cost of adding a small OIR telescope to an existing γ-ray instrument. The space instrument would achieve several times the ground detection rate, but have vastly superior observing conditions. **These arguments clearly justify a space platform.**

Number of Channels Below ν_a, synchrotron must have a log slope[2] α_0 of 5/2 (cases I, II, where above ν_a the slope is the same as that in the X-ray band) or 2 (cases III,IV, where above ν_a slope = 1/3). Consider three channels, c_1, c_2, c_3, measuring two slopes, α_{12} and α_{23} at lower and higher frequency (see **Figure 1** for cases III & IV; c_1, c_2, c_3 are shown as H, R, and B filters.). If $\alpha_{12} = \alpha_{23} =$ (5/2 or 2), all channels are below ν_a; if $\alpha_{12} = \alpha_{23} \neq$ (5/2 or 2), then all channels are above ν_a (top panel). If $\alpha_{12} \neq \alpha_{23}$ and $\alpha_{12} \neq$ (5/2 or 2; mid & bot. panels) then ν_a must be between c_1 and c_2. Because measurement of any one of these slopes (5/2, 2, 1/3, or X-ray slope) gives the other for all cases, ν_a may be solved for. Additional channels, however, allow the measurement of deviations from assumed synchrotron power laws, and better constrain slopes. We therefore specify ≥ 4 channels.

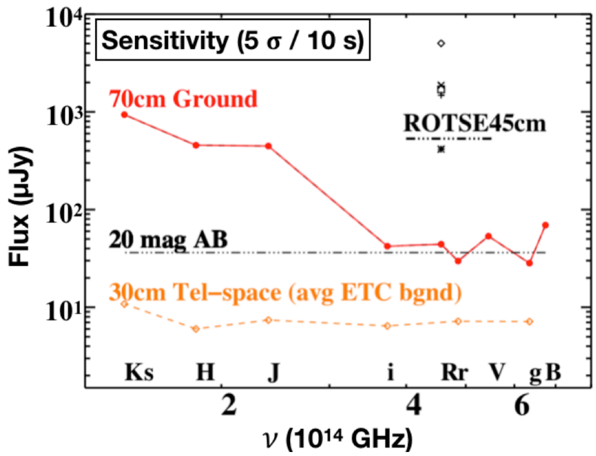

Figure 2 Sensitivity in 10 s. The 30 cm space telescope is by far the most sensitive. Filter frequencies are as labeled just above the x-axis. The ROTSE average single channel sensitivity is given by the line just below its label; symbols give the prompt detections from [6] (but two are off the top edge of the plot).

High time resolution allows correlation of the OIR light curve (LC) with the γ LC, in order to test a common mechanism for the two measurements, and to study rapid evolution in POSS. This is problematic with CCDs, because read noise dominates short exposures. If long exposures are used to obtain good sensitivity, then short timescale information is lost. Electron-multiplied CCDs, however, multiply the electrons from the sensor before readout, boosting the signal far above the read noise, so this contribution is negligible. Short exposures (~ 0.1 s) can therefore be used, regardless of target brightness, as more frames can be co-added until a detection is made, optimizing time resolution vs. SNR.

2.1 Performance

In Figure 2, we used average space backgrounds from the Hubble Exposure Time Calculator to estimate performance. Though bright bursts would provide ~ 300 ms time resolution, we assume here data co-added in time to 10 s bins, and 1024 X 1024 1" pixels to cover a relatively large 17' field with a modest data rate. Superimposed on the diagram we plot ROTSE-III detection brightness[6]; the proposed instrument goes ~100X deeper.

3 POSS Science

3.1 A POSS Catalog for GRB Population Studies

The POSS instrument will produce a catalog of time-resolved, multi-channel OIR LCs, associated with the γ-ray data on the same GRB (often from several instruments). GRBs are notoriously heterogeneous; in order to span and quantify a significant range of behavior, we propose POSS data for ~ 100 GRB over the mission. From the OIR data (galactic and local extinction corrected, the latter via AG observations), power law slopes would be measured, and where possible, a value of ν_a. Together with the γ band power law slope below E_{peak}, the synchrotron emission case (or other mechanism) would be given for single-component spectra. The time-correlation of OIR and γ-ray LCs, to model multi-component spectra, is a powerful capability. While [2] listed several single-component GRBs, others, e.g. 080319B are multi-component. The 110205A opt-UV LC correlated better with MeV than the ~100 keV LC, suggesting a second, higher E_{peak} component[13]. Though only speculation, we ask the reader to consider the following as a possible application of component separation: Correlations of E_{peak} vs. luminosity are of limited use as a cosmological tool because of the large scatter. What if the correlation was excellent for either component individually, but the *averaged* fit had large scatter? Understanding muilti-component bursts has applications to understanding a wide range of GRB properties.

Studies of the properties of each emission mechanism vs. other GRB properties (luminosity, duration, E_{peak}, spectral lag, etc.) would illuminate the relation between the macroscopic models and the microphysics, adding information about dissipation processes for the GRB jet energy. These studies would yield important insights into the physics of GRB jet formation, structure, and emission.

3.2 Short GRBs *Can* be Measured

GW170817 confirmed the different (merger) origin of at least some Short GRBs (SGRBs), adding to differences in spectral slope and spectral lag. And yet, 40% of SGRBs have weak but long-lasting "extended emission" (EE) similar to that of LGRB[14]. Do SGRB jets then often last as long as in LGRBs, radiating less? Our POSS instrument is too slow to observe SGRBs, but catching the EE phase will teach us about properties common to both types, and late time properties such as envelope solid angle coverage and opacity vs. time in early phases that are very important for understanding SGRBs.

3.3 Additional Science

Very rapid **destruction of circumburst dust** by an early optical-UV flash would be observed as early color and brightness evolution with a duration ~60 s[15,16], as the radiation "burns" away the dust, changing the color from extremely red to blue with the brightening optical emission. This would explain why ubiquitous high N_H is observed in GRB AGs (often ~10^{22} cm^2; [17, 18, 19, 20]), even though optical extinction is low[21]. Note that *only the dust local to the GRB* would be destroyed, allowing separation of local and host galaxy dust effects, allowing the study of dust in individual star systems *independent of large-scale dust*, *to high redshifts*. **Galactic Transient Sources** also have rapid X–γ events problematic for ground-based response. High time resolution for such rapid variations, and NIR coverage for extinguished galactic plane sources would be ideal for this science. **High-z GRB studies** would benefit from the photo-z capabilities of multiple channels: prompt images yielding high photo-z (GRB or host) could trigger rapid-response by the largest telescopes, getting spectra while the GRB was still bright.

4 Conclusions

Several instruments capable of detecting and localizing GRB are proposed or in development, e.g. those missions given in section 1.3, plus Strobe-X (an X-ray timing mission with GRB localization capability). None of these missions now plan a POSS-capable OIR instrument. While we respect the primary science of these missions, we find that their cognizant agencies did not sufficiently consider the scientific importance of adding POSS capability. Our call to action for such consideration is *timely*, because of the decades timescale for space missions: If this capability is not added to missions in development now, the opportunity will be lost for a generation.

Emission Mechanism Endgame Despite expectations, Fermi showed no evidence for high-energy SSC, eliminating this possible mechanism. For non-thermal, Band function spectra, the synchrotron process seems to be the only viable emission mechanism left. In the case of single-component dominant GRB then, we can finally say we have a clean, well-defined experiment to identify the mechanism, confirming the prediction, or not: synchrotron emission can only produce power laws in the OIR with log slopes of 5/2, 2, 1/3 or the same slope as is present in the X-ray bands[2]. For such cases with good slope measurements (including extinction and other corrections), with enough channels to verify that the slope of a single power law segment has been measured (i.e. ν_a is not between filters, or in one of them), this is then a powerful, clear test. For other spectra, (added synchrotron, photospheric, or other components), correlation of the optical and γ-ray emission would allow us to analyze only the OIR-γ linked component in a similar way. It would be a great loss for the astrophysics community to miss this clear-cut opportunity to solve such an outstanding problem, without any other possible resolution for decades.

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