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The New Ultra-Fast Flash Observatory-100: measuring GRB UV-IR emission starting 1 ms after trigger

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Abstract. MEMS mirror arrays fabricated at the Research Center for MEMS Space Telescopes (RCMST) of Ewha Woman's University, Seoul, can point over >60 degree fields within 10^{-3} s. Such devices can therefore steer a telescope beam for much faster response to GRB triggers than ever before. The Ultra-Fast Flash Observatory (UFFO) concept uses an X-ray coded mask camera to trigger a MEMS mirror array to point an optical/IR telescope at GRBs. The UFFO-Pathfinder, with a 10 cm telescope mirror, is scheduled for space launch in Nov. of 2011, and should detect dozens of GRB over its lifetime. In 2015, we plan to launch the UFFO-100, with a 30 cm telescope and an X-ray camera with 1000 cm^2 of collecting area. Two cameras will simultaneously measure emission in B to V and a R to near-IR (NIR) bands. The UFFO-100 will detect ≥ 29 GRB in the NIR in 10 s exposures, including extinguished GRB, and can measure dust destruction. These advances in response time and instrumentation will enable UFFO to do a large, systematic study of the rise shape of GRBs for the first time. In this paper we describe our instruments and some relevant science.

Key words. Gamma-Ray Bursts: Observations – Instrumentation: Optical – Instrumentation: X-ray

1. Introduction

Prompt γ-ray burst (GRB) *optical* emission, the rise phrase of the optical light curve, comes from processes related to the explosion (not the afterglow), and relates to a variety of interesting physics. Current instruments, however, are limited in their ability to study this emission, because they do not respond fast enough, usually taking longer than 60 s after GRB trigger to acquire data. Below, we discuss rapid response physics, and our space instrument development program to provide rapid-response optical observations.

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2. Prompt Emission Measurements

The bulk Lorentz factor Γ of emitting material can be estimated from the time of the emission peak (Molinari et al. (2007)). Fermi has measured Γs > 10^3, but such high values are considered problematic. It would be valuable to measure Γ independently from optical emission, however, one would then need to measure peaks in 10 s or less from the onset of the explosion. We need much faster response than is currently available.

We have observed prompt X-ray emission to have fast variability, which supports the internal shock model. If we had the time resolution to measure varibility for optical emission, we could see if it was from the same mechanism. We need higher time resolution, and faster response.

When we can see correlation between prompt optical and X-ray emission, this is strong evidence that they come from the same emission region and process. There are both examples, 080319b (the Naked Eye Burst; see optical and X plot figure in (Racusin et al. (2008))), 041219, and a counter-example with no correlation, 990123 (Vestrand et al. (2005)). Only the 080319b data are very good. We need faster response to provide more examples.

There is a great deal of physics in "multi-messenger" measurement of gravitational wave (GW) signals and optical to γ light, in the case of the putative short GRB progenitors. When sensitive GW systems are in place, they will require optical ID and red shift (Nishizawa, et al. (2011)). Short GRBs are faint, but have not been observed at their peak; observing them sooner, near peak, should yield more detections. In addition, there would be exciting new physics in the correlation of the GW and photon light curves. The timescales of these systems could be quite short - so faster response is desirable.

GRBs are the ideal testbed for alternative GR models. Not only is the same object and process responsible for emission over many decades in ν from far-IR to γs, giving an ideal test for dispersion, but the same test can be compared among GRB over a huge range in z. However, to catch the simultaneous, prompt emission, again, we need fast response and high time resolution.

GRBs have enough energetic photons to vaporize dust throughout a typical circumstellar dust cloud (e.g. (Salvaterra et al. (2009))). This means that we could watch the dust evaporate, dynamically, by looking at the ratio of measurements in the blue and NIR bands. However, the time scale for this is expected to be ∼ 60 s (e.g. (Perley et al. (2010))) so, again, we need faster response.

(Panaitescu & Vestrand(2008)), in their survey of early measurements of GRB light curves, have shown that the peak *optical* luminosity correlates with the optical rise time. This brings up the exciting possibility that GRB may be a kind of "calibratable standard candle", that they may be used to do cosmology to extreme z. The problem is that of their sample of 30 light curves, only 12 have a peak measurement. Most of the rise times are unknown - the data thus far are insuffcient. Faster response is needed, fast enough to catch the optical rise in a large sample.

2.1. Limitations of Swift+GCN

Swift has produced hundreds of GRB light curves thanks to its relatively fast response. However, This response is strictly limited: there is a hard minimum of around 60 s for UVOT to respond to a GRB (Grossan et al. (2011)).

Ground-based telescopes such as ROTSE-III have made some dozen or so published sub-60 s measurements. (Rykoff et al. (2009)) gives a survey of these, some with response times as rapid as ∼10 s after trigger. However, of the sub-60 s responses, only one rise time was measured. Fast telescopes necessarily have small mirrors to be fast, and are therefore not very sensitive. The result is a small, biased sample, and no short GRB measurements. Faster response and greater sensitivity are required.

Future Prospects for the GRB Rise Phase Measurements The early light curve data on the Naked Eye Burst 080319b are simply thrilling. However, there will never

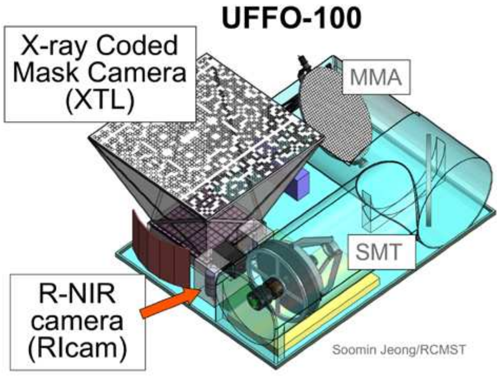

Fig. 1. UFFO-100 rendering in a compact configuration.

be a large sample of such measurements. We have had *one* burst this bright in swift's life, ~six years now. The high-resolution prompt optical light curves are from Tortora (Beskin et al. (2010)), a super-wide field instrument. With a sensitivity limit of 9th mag, such instruments can *only* measure the very rare ultra-bright bursts. Swift is very old and is unlikely to measure many more such rare events. We need a new instrument and space mission to deliver a significant sample of optical rises.

3. Respond Faster - The UFFO Program

Swift gets a fast, crude location from the BAT X-ray camera, then slews to point the UV-optical instrument (UVOT) on target. A finite time is required to slew the massive spacecraft, and more for it to settle. We have a much faster method: Steer the beam, not the spacecraft. Here one puts a tilting reflector in front of a telescope, simply redirecting the input beam to the desired target. Our reflectors can point up to 10,000 times faster than Swift.

Il Park and his group at Ewha Womans University have developed a unique micro-electro-mechanical (MEMS) micromirror arrays (MMAs; (Park et al. (2008))) that can point and +40 to -40 deg. in two dimensions, and settle in ~1 ms, with ≥ 90 % fill factor. These devices have already flown in space investigating transient atmospheric phenomenon on the Tatiana-2 mission, and are ideal for fast-response GRB observations. The current generation devices have a drawback, however: the PSF is smeared to 2′FWHM, due to the non-uniformity of pointing. We have a development program in place to improve this.

At the same time, we have developed low-mass mirrors on gimbals, which point over the same areas of sky, and settle in one second, with no PSF degradation. We have also developed a hybrid MMA/gimbal system, a mosaic of MMA devices mounted on a gimbal platform. On trigger, the MMAs direct the telescope beam for a short period, e.g. 1 s, for high-time resolution measurements. After this ultra-fast response, the gimbal is then commanded on target, while the MMA is commanded flat; in this mode there is no PSF distortion and maximum instrument sensitivity results. The hybrid system gives both ultra-fast mode, and maximum sensitivity mode with only small down time in between, and at a time chosen by the observer. Our program of developing beam-steering telescopes, coupled with an X-ray location and trigger instrument for GRB observations (like Swift), is called the Ultra-Fast Flash Observatory (UFFO) program.

The Pathfinder Mission Through our collaboration with Moscow State University (MSU)/SINP on Tatiana-2 and other missions, we were offered a place on the Russian Lomonosov mission, scheduled for launch November 15. With a short time to launch, we chose to build a very modest instrument, but one that will still have a significant number of GRB detections. For GRB, the Log N vs. Log S curve *flattens* at small S. Therefore, If all you need is a GRB *detection*, rather than high time resolution, a good spectrum, etc., a *much* smaller instrument than Swift BAT can still detect many GRB per year. Our UFFO-Pathfinder instrument (Park et al. (2010)), has only a 20 kg mass budget. The coded-mask X-ray camera, the UBAT, has 190 cm^2 collecting area /1.3 Sr FOV, and the optical telescope telescope has a 10 cm aperture. We expect to detect about 40 GRB, and about 10 optical counterparts each year.

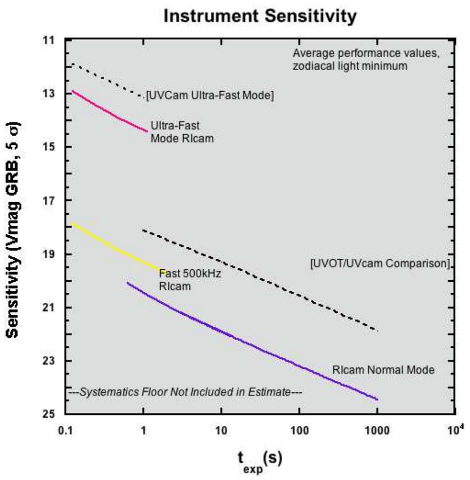

Fig. 2. UFFO-100 sensitivity in equivalent V band magnitude, typ. GRB spectrum.

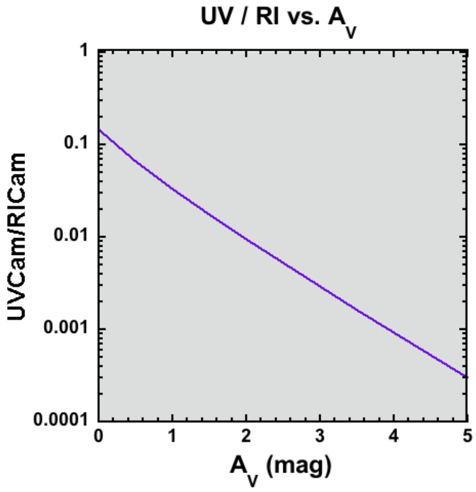

Fig. 3. Ratio of UV-optical to optical-IR band as a function of dust extinction.

3.1. UFFO-100 Launching 2015

We have now finished our design for the UFFO-100 mission, a 120 kg instrument to fly on the NUCLEON spacecraft on a Soyuz launcher in 2015, in collaboration with MSU / SINP. This instrument features a 30 cm aperture optical instrument and an X-ray camera with 1000 cm^2 of CZT collecting area and 1.4 Sr FOV (Fig. 1).

The telescope (the SMT) features two optical paths split by a dichroic. The blue arm, 0.57 down to 0.2 μm, has an intensified CCD detector for very high time resolution. The red arm, 0.57 to 1.7 μm, has a HgCdTl sensor, cut off at 1.7 μm to reduce thermal background. The camera optics feature a lyot stop and Narcissus baffles for extremely low background without a dewar, as the sensor sees only cold sky or reflections of itself, cooled to cryogenic temp.s. With a very efficient H2RG sensor, the extremely wide band from 0.57 - 1.7 μm, low background, and the steeply falling spectrum of GRB, this makes for an extremely sensitive instrument, as shown in Fig. 2.

With two cameras, we will measure a broad-band spectral slope; further, it will be possible to measure dust evaporation dynamically, by following the optical-to-NIR slope in time (Fig. 3). Alerts from the UFFO-100 will be broadcast on the GCN for community follow-up for spectroscopy, etc.

We predict ~64 GRB/yr. in X-ray (~5 short GRB), with ≥29 NIR detections ($t_{exp} = 10s$). We will measure GRB starting sooner than ever before; we may measure some at peak for the first time, perhaps brighter than previously known, for even higher detection rates. This would be important for short bursts, which are faint, and still have few detections.

4. Conclusions

Fast-response beam-steering technology makes it possible to observe the rise phase of GRB emission, opening up an new window on GRB physics. Look for our observations after our missions at the end of 2011 and in 2015.

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