Exploring the First Minute: New Technology for Measuring Color and Polarization Variations in Prompt Optical Emission

W. T. Vestrand*, D. J. Casperson*, C. Ho*, E. Raby†, R. Shirey*, D. Thompson†, R. R. White* and J. Wren*

*Los Alamos National Laboratory, ISR-2, MS B244, Los Alamos, NM 87545, USA
†Los Alamos National Laboratory, P-21, MS D454, Los Alamos, NM 87545, USA

Abstract. With the coming launch of the Swift satellite, there will be many new opportunities to study the physics of the prompt optical emission from gamma ray bursts with robotic ground-based telescopes. We discuss a new imaging system under development at Los Alamos National Laboratory that will provide simultaneous multicolor photometry of the rapidly evolving prompt optical emission in the first minutes after a burst trigger. This next generation system employs state-of-the-art photon-counting imaging technology at the focal plane of a rapidly slewing telescope. The imaging sensor is composed of an S-20 photocathode, stacked microchannel plates, and crossed delay line readout electronics that together are capable of measuring the time of arrival and positions for individual optical photons with 200 picosecond time resolution. The imager is coupled with electronically tunable liquid-crystal filters to provide essentially simultaneous linear polarization and multicolor photometric measurements of the prompt optical emission from a gamma ray bursts.

INTRODUCTION

To understand fully the evolution of prompt optical emission from gamma ray bursts (GRBs), one needs the ability to make simultaneous multi-color photometric observations during the first minute after the cataclysmic explosion. The extreme ultra-relativistic nature of the outflow means that the complex history of interactions and the deceleration of the bulk flow, which occurs on the timescale of a day in the plasma frame, is carried by emission that arrives at Earth within the span of a minute. During that rapid deceleration, there are important parameters that define the physics of the flow: the Lorentz factor, the ambient density, the fraction of the energy in mass of the particles, and the fraction of the energy in the magnetic field. By measuring simultaneously the spectral shape of the emission and how it evolves, each of the parameters can be determined [1]. Measurements of the spectral evolution during the first minute are therefore a powerful probe of the physics of the largest explosions since the Big Bang.

But studies of the spectral evolution of GRB emission at optical wavelengths must correct for spectral variations generated by material along the line of sight to the GRB. There is evidence that long duration GRBs are associated with star formation regions and that visual extinction along the line of sight is likely to be in the range of $A_V = 1-2$ magnitudes with values all the way up to $A_V = 5$ magnitudes or greater (e.g.[2, 3]). Further, the prompt optical-UV flux from a GRB explosion is sufficient to destroy the dust column within tens of seconds after the burst (e.g., [4]), producing strongly variable extinction and reddening. So to infer the intrinsic spectral and temporal evolution of a GRB explosion in its first minutes, the effects of the variable dust screen have to be measured. If the extinction law throughout the evaporating column has a fixed wavelength dependence, any shift in color-color space orthogonal to the reddening vector is intrinsic spectral evolution. So simultaneous photometry in three or more colors will enable the separation of color changes due to variable reddening from intrinsic spectral variability.

Another important diagnostic of the physical conditions in the ultra-relativistic burst plasma is the polarization of the optical emission. Since the prompt optical emission is believed to be synchrotron emission, it should be intrinsically linearly polarized. Polarization measurements have been made of the optical afterglow ten hours or more after the event and have shown linear polarizations of $\sim 1-3\%$ that can temporally vary in amplitude but show no variation in polarization position angle (e.g. [5]). However, new estimates indicate that the prompt emission could have polarization fraction as high as $\sim 60\%$, if the ordered magnetic field is advected into the relativistic plasma from the GRB progenitor[6]. Observations of polarization in the prompt optical phase and its variation both in amplitude and in position angle will therefore provide important clues about the geometry of the cataclysmic event and the interaction of burst plasma with the surrounding medium.

PHOTON-COUNTING MULTICOLOR PHOTOMETERY

At LANL we have constructed a new class of photon counting imagers with extremely high time resolution for astronomical applications. These imagers are composed of a photo-cathode, a stack of three micro-channel plates, and a crossed delay line (CDL) readout all hermetically sealed in a vacuum tube (see Figure 1a). When used for the detection of optical photons, we employ an S-20 photocathode, which has a quantum efficiency that allows effective detection of optical photons up to wavelengths of about 750 nanometers. Each photoelectron ejected by the photocathode generates a cascade in the micro-channel plate (MCP) stack that produces a gain of $\sim 10^7$. The emergent electron cloud spreads over about 10 wire pairs in the tightly wound CDL grid allowing centroiding of the event to better than 100 microns on the 40 mm diameter active area.

This sensor tube assembly is connected to ultra-fast electronics that measure individual photon arrival times with a time resolution of 200 pico-seconds and provide a throughput of more than 10^6 counts per second. This combination of imaging capability and unprecedented ability to detect individual optical photons with extremely high time resolution has already led to important applications of this technology for time-resolved imaging of cloud scattering and 3-D ranging and mapping of solid objects [7].

Like a conventional CCD imager operating at optical wavelengths, our photon counting imager employs a multicolor filter system to derive spectral information about the incident emission. But for studies of prompt GRB emission during the first minute, mechanical filter wheels are too slow. Instead, to obtain quasi-simultaneous multicolor photometry, a large aperture (35 mm square), electronically tunable, optical filter is located in front of the imager. The filter is a liquid-crystal tunable filter (LCTF) that is essentially a multistage Lyot-type polarization interference filter with an electronically controllable liquid-crystal waveplate in each stage to provide variable retardance. This LCTF is capable of switching between three broadband filters with no moving parts or vibration in under a millisecond. A controller is used to continuously cycle through the filter set at a rate of 1 Hz or faster. This filter/imager combination therefore time-tags and color-tags all detected photons yielding essentially simultaneous multi-color photometry.

Unlike a conventional CCD imager when used for ultra-high cadence imaging, our imager is essentially free of detector and read noise. The detector noise level for our photon counting imager is determined by thermal electron emission from the photocathode. At room temperature these electrons generate typically only a few thousand counts/s distributed randomly across the MCP face yielding a noise count rate of $\sim 10^{-2}$ per second per pixel. These rates are negligibly small compared to the available counting rate of 10^6 per second. Our imager has the ability to operate at room temperature with a sensitivity that is limited only by the natural sky background and the available photon statistics.

PHOTON-COUNTING POLARIMETRY

Another advantage of the LCTF technology is that it is intrinsically sensitive to the polarization properties of the incident radiation. When another electronically controllable stage is placed in front of the color filter, it is possible to select the color and linear polarization state of the photons that pass through to the imager. The rapid electronic switching possible with this system means that one can rapidly sample the spectral distribution and polarization properties of the prompt emission. The photon arrival time, position, color, and polarization are measured for all positions in the imager's field of view. As a result, one automatically gathers simultaneous "control" measurements of other objects in the field as well as insure that transients, whose locations are often only known with arcminute accuracy, are measured. The primary limitation of this approach is that the multiple stages of filters allow a very small fraction of the collected photons to be detected. As result, such detailed observations of polarization and spectral evolution during the first minute will only be possible for the very brightest optical transients.

APPLICATION TO THE FIRST MINUTE OF GRBS

Most models assume that the optical emission from GRBs is synchrotron radiation generated by energetic electrons in the burst outflow. Figure 1b shows the light-curve measured for GRB990123 [8] which, while it is only composed of four widely spaced points during the first few minutes of the burst, is still the most complete set of measurements available for prompt optical emission. By noting that the optical and gamma ray intensities were not correlated, many authors have argued that the emission in the two bands originated in different regions and suggested that the prompt optical outburst is generated as a reverse shock that traverses the relativistic outflow. Such a reverse shock can only occur once in a given GRB, and indeed, the ROTSE data seem to show a single peak followed by power-law decay. On the other hand, some models claim that rapid optical variations were present that should be correlated with the gamma ray fluctuations that were as short as tens of milliseconds in this event (e.g. [9]). Unfortunately, the lightcurves obtained by conventional CCD imaging will be too highly under-sampled to definitively distinguish between the models.

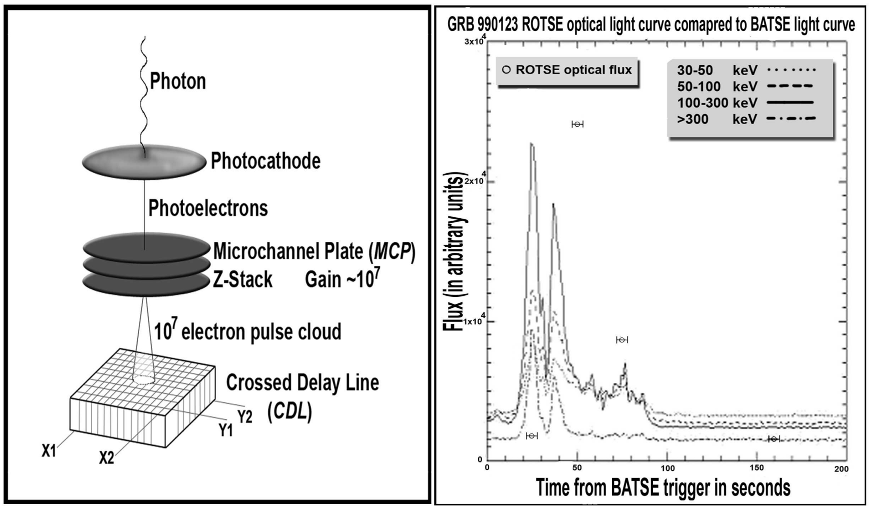

FIGURE 1. The panel on the left shows a schematic of the layout of the photon-counting imager. The panel on the right shows the gamma ray lightcurve and the four broadband optical lightcurve measurements of the optical flash from GRB990123.

The launch of the Swift satellite in the summer of 2004 will provide an exciting new opportunity to study the prompt optical emission from GRBs by providing accurate, real time, positions for roughly 100 GRBs per year. The Swift satellite will be able to reorient itself in a median time of just over 50 seconds and begin measurement of the prompt optical emission with a sensitive onboard UV/Optical Telescope. But to make measurements in the first minute, one will need a rapidly slewing ground-based telescope. One of our photon counting imagers will be deployed on a RAPTOR 0.4-meter telescope with a fully robotic rapidly slewing mount. The robotic mount is connected via socket to the GCN network for prompt response to GRB alerts and capable of pointing the telescope to any direction in the sky in only four seconds. When deployed on that telescope, the field of view for the imager is $12'$x $12'$. Operated without the LCTF, the system has a predicted 3-sigma sensitivity of $V \sim 19^{th}$ magnitude in 10 seconds. In an event as bright as GRB 990123 the system can measure fluctuations as short as a few milliseconds when operated without the tunable filter in the optical path. Such observations would be a powerful probe of the physics during the critical first minute.

REFERENCES

1. Wijers, R. and Galama, T. , *ApJ* **525**, 177 (1999).
2. Paczynski, B., *ApJ* **494**, L45 (1999).
3. Lamb, D.Q., *Phys. Reports* **333**, 505 (2000).
4. Waxman, E. and Draine, B., *ApJ* **537**, 796 (2000).
5. Covino, S., et al., *A&A* **404**, L5 (2003).
6. Granot, J. and Konigl, A., *ApJ* **594**, L83 (2003).
7. Ho, C., et al., *Appl. Optics* **38**, 1833 (1999).
8. Akerlof, C.W. et al., *Nature* **398**, 400 (1999).
9. Liang, E. et al., *ApJ* **519**, L21 (1999).