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Instrumentation of LOTIS: Livermore Optical Transient Imaging System; A Fully Automated Wide-Field-of-View Telescope System Searching for Simultaneous Optical Counterparts of Gamma-Ray Bursts

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A Fully Automated Wide-Field-of-View Telescope System Searching for Simultaneous Optical Counterparts of Gamma-Ray Bursts

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ABSTRACT

LOTIS is a rapidly slewing wide-field-of-view telescope which was designed and constructed to search for simultaneous gamma-ray burst (GRB) optical counterparts. This experiment requires a rapidly slewing (< 10 sec), wide-field-of-view (> 15°), automatic and dedicated telescope. LOTIS utilizes commercial tele-photo lenses and custom 2048 x 2048 CCD cameras to view a 17.6 x 17.6° field of view. It can point to any part of the sky within 5 sec and is fully automated. It is connected via Internet socket to the GRB coordinate distribution network which analyzes telemetry from the satellite and delivers GRB coordinate information in real-time. LOTIS started routine operation in Oct. 1996. In the idle time between GRB triggers, LOTIS systematically surveys the entire available sky every night for new optical transients. This paper will describe the system design and performance.

Keywords: wide-field-of-view telescope, automatic telescope, gamma-ray bursts

1. INTRODUCTION

The origin and nature of gamma-ray bursts (GRBs) remains an important unresolved problem in astrophysics[1]. GRBs are brief bursts of gamma-ray radiation that appear at random positions in the sky. Much of the difficulty in studying gamma-ray bursts results from their short duration (< 100 sec) and the poor directional precision (1 ~ 10° 1-σ statistical error) available from current orbiting gamma-ray detection experiments such as BATSE on the Compton Gamma Ray Observatory. Recently an Italian-Dutch satellite (BeppoSAX)[2,3], has observed three GRBs with possible fading X-ray and optical counterparts[4,5]. These counterpart observations were made many hours after the GRBs. While these events gave data on their distance scale[6] and their interaction with interstellar medium, their actual production mechanism is still very unknown. An observation of an optical signal simultaneous with the GRB, and its light curve, can provide crucial clues to this mechanism of GRBs.

In an attempt to make such observations, we initiated an ambitious and innovative experiment to search for simultaneous optical radiation associated with GRBs. The first instrument utilized an existing wide field-of-view telescope (60° field-of-view with 23 fiber coupled intensified CCD cameras on a rapidly slewing Contraves index table) at Lawrence Livermore National Laboratory (LLNL) programmed to respond to real-time coordinates issued by the GRB Coordinates Network (GCN[7]). This first generation instrument did not find any evidence for optical activity dimmer than $m_V > 7.5$[8]. We constructed a second generation experiment with 250 times higher sensitivity than the first. This experiment is called LOTIS (Livermore Optical Transient Imaging System) and has been operating since October 1996.

The design requirements for LOTIS were: 1) > 15° field-of-view in order to cover the error circle of the rapid GRB alert derived from the satellite telemetry; 2) the capability of pointing to a position in the sky in < 5 sec since most of the bursts last < 100 sec ; 3) a high sensitivity in order to set tight constraints on GRB models; 4) a light weight in order to have fast slewing; 5) and a low cost. With careful optimization we were able to design and construct the entire system within a year. This paper describes some details of the components of this system.

2. LOTIS OPTICS

In order to have the required field of view we needed very short focal length optics. We chose a commercial telephoto lens, the Canon EFL f/1.8 which has a focal length of 200 mm. With our 3.1 x 3.1 cm CCD focal plane the Canon lens gives an 8.8 x 8.8° field-of-view. Their unique multi element design, correcting both spherical and chromatic aberration, produced higher optical quality for stellar point sources than other similar lenses available commercially in our tests utilizing a table-top off-axis collimator and night sky images. Gaussian fits to the image of point sources with the Canon lens yielded 1-σ widths of 0.4 pixels.

3. LOTIS CCD CAMERA AND READOUT ELECTRONICS

The LOTIS cameras use Loral 442 CCDs which are commercially available at affordable prices in various classes based on their defect quality. We developed readout electronics using lower quality CCDs and replaced them with higher quality ones for astronomical observations. These CCDs have 2048 x 2048 pixels each with 15 x 15 µm size providing a focal plane area of 3.1 x 3.1 cm.

The readout electronics was designed and fabricated at LLNL. Figure 1 shows a block diagram of the LOTIS camera readout electronics. It is composed of a stacked array of 3 PCBs (Printed Circuit Board) and the camera housing. The three boards are the CCD board, the ADC board, and the Computer Control board. The housing provides a mounting mechanism for the electrical connectors, cooling fan, shutter as well as a means of mounting the camera to the telescope.

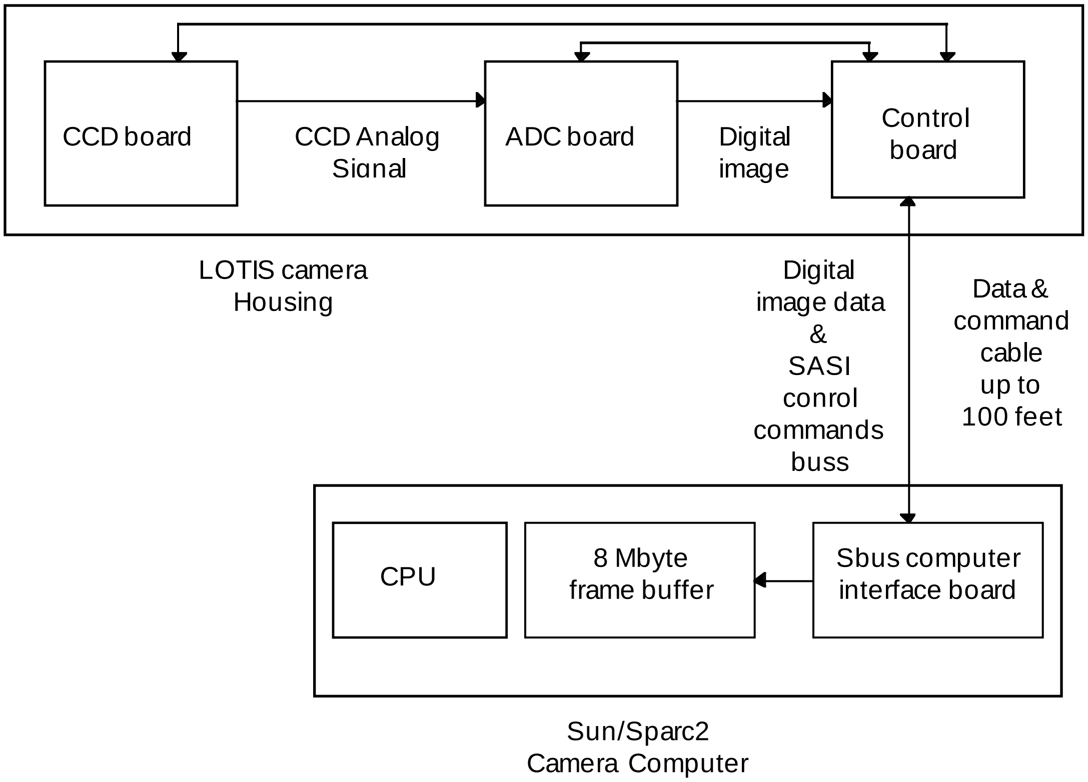

Figure 1. LOTIS Camera Readout Electronics Design

The CCD board is composed of three parts. There is a socket for the Loral CCD imager, CCD clock drive circuitry, and the first stage CCD signal amplifier/buffer. The clock drive voltages are regulated and the levels are resistor programmable. This feature was used several times as new batches of CCDs were purchased requiring different clock voltage levels. The CCD signal amplifier provides the first stage of gain from the CCD. The amplifier gain value was selected for the desired sensitivity from the CCD. The amplifier provides a low impedance drive of the CCD signal which is routed to the ADC board. The CCD board also provides temperature monitoring of the CCD.

The ADC board provides the second stage of CCD signal amplification, CDS (Correlated Double Sampling) circuit, and ADC (Analog-to-Digital Converter). The 12 bit ADC sampling rate is fixed at 500K samples/sec as a compromise between low noise operation and speed of reading out of the CCD. At a read out rate of 500K pixels/sec it takes 8 sec to read out the 4 million pixel image from the CCD. The parallel digital output of the ADC is buffered and routed to the Control board. The ADC board also converts the analog temperature data of the CCD to digital and routs it to the Control board.

The Control board provides all the control signals for the CCD and ADC boards. The Control board also serializes the CCD pixel data and sends it to the host computer. The Control board accepts a suite of commands from the camera computer and returns status information about the camera via a modified SASI (Synchronous Addressable Serial Interface) serial buss protocol. The SASI protocol is an 8 bit serial buss and was modified to 16 bit command/status words. The control board receives the parallel image data from the ADC board and serializes it then sends it to the host computer over a separate buss at 6 Mega bits/sec rate. No portion of the image data is stored in the camera.

The mating interface from the camera control board on the camera to the camera computer is a custom SBUS card with PLDs (Programmable Logic Devices). A pair of Altera PLDs are programmed to handle the user specific commands and control functions. These are easily changeable to accommodate new or modified camera requirements. Some computer controllable functions are: 1) integration times; 2) data transfer enable/disable; 3) video enable/disable; 4) FPA temperature measure; 5) Bias level (offset) control; 6) shutter control; 7) fast flush; 8) test gray pattern generation.

The camera housing is approximately a 6 inch cube. It contains the cooling system for the electronics and CCDs and a mechanical shutter mounting fixture. We use Melles Griot 53 mm aperture shutters for our cameras. The CCD board is mounted with 3 spring loaded 100 turns/inch screws from the front panel allowing us to adjust the CCD focus including tip and tilt. The various component of the camera are shown in Figure 2.

Figure 2. The LOTIS camera/lens assembly. The first panel is a Loral 442 2048 x 2048 CCD. It has a 3.1 x 3.1 cm imaging area. The second panel is the set of 3 CCD readout electronic boards. The third panel is an assembled camera with a Canon f/1.8 200 mm lens.

4. TELESCOPE MOUNT, HOUSING AND SITE

To obtain the > 15° field of view necessary to cover the GRB trigger error box, we constructed a 2 x 2 array of LOTIS cameras resulting in a total field of view of 17.4 x 17.4°. The 4 cameras overlap 0.2° in each dimension. The cameras are mounted on an equatorial mount manufactured by Epoch Instruments, CA. This mount can point payloads up to 50 lbs to any part of sky within 4 sec. The mount has 15 arcsec/min tracking stability and 0.01° absolute pointing accuracy. The performance of the mount is well matched to the camera resolution for 10 sec exposures .

Each camera was focused in the lab using an off-axis collimator with a pin hole whose angular substance was much smaller than a pixel (15 arcsec/pixel) angular size. This off-axis collimator has a focal length of 5 m and was used with a 100 µm pinhole. We adjusted the focus knobs at all 4 corners of the CCD and the center. Because of the short focal length of the lens, the focal depth was ~120 µm equivalent to a half turn of the focus screw. At each location of the CCD, the pin hole image was fitted to a Gaussian shape and the fitted sigma value was used as a figure of merit to produce the best flat focus across the focal plane array. After installing the cameras outside, we repeated the procedure using stars to validate our focus procedure in the lab.

The telescope is housed in a clamshell that permits sky coverage down to 20° above the horizon. An electromechanical actuator by Duyff-Norton, NC, which is capable of 1500 lbs load, opens and closes the top shell. The bottom part of the housing has a 19” wide electronic rack with the mount controller, power supplies, an Alan Bradley industrial controller, and a small air conditioner to keep the electronics and cameras cool during the hot and dry summer days.

LOTIS is located at Site 300, LLNL’s remote test facility, 25 miles east of Livermore, CA. We chose this site for easy access, established infrastructure, and because it has a much darker sky than the Livermore city. The four camera assembly on the mount, and the final assembled system at Site 300 are shown in Figure 3.

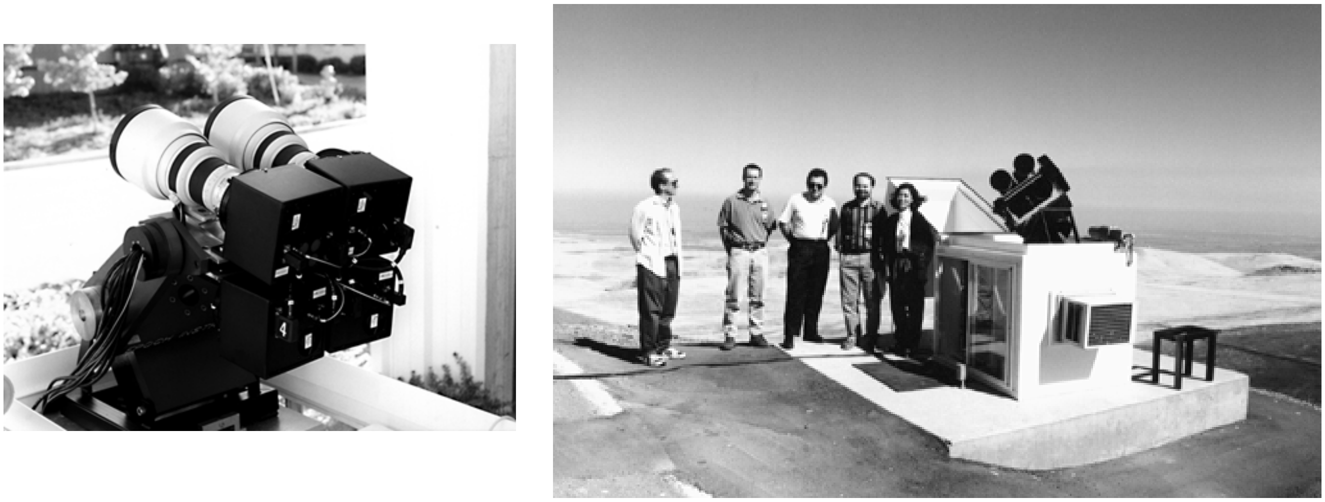

Figure 3. Assembled 4 LOTIS camera system on a rapidly slewing mount and the LOTIS system at Site 300 near Livermore, CA.

5. LOTIS DATA ACQUISITION SYSTEM AND ON-LINE SOFTWARE

Figure 4 shows a block diagram of the data acquisition system. The system is as modular as possible for easy maintenance. The system includes many features required for reliable remote automated operation. Besides the computer controllable mount and electro optical sensors, the system has computer controllable housing, various diagnostic sensors and an UPC to handle power failures. LOTIS is fully automated: it starts automatically at night; opens the telescope housing; initializes the hardware; starts surveying the night sky systematically; responds to gamma ray burst coordinates within 5 sec when triggered; archives data after the night’s observation; analyzes diagnostic data then notifying us of the status of the night’s run by e-mail, and handles various failure modes which happened many times including power outage, cable wrap around and tape errors.

The LOTIS on-line software has three major components: the communication link to the GRB Coordination Network (GCN), the telescope management code, and the camera control and image acquisition code. The LOTIS computer system consists of a network of five SUN SPARC computers, one computer for the supervisory functions and one computer for each of the four cameras. The host computer is a SUN/SPARCstation10 and the camera computers are SUN/SPARC station2's.

The communication link and the telescope control software run on the host computer. The communication link code has an Internet socket connection to the GCN distribution computer in NASA/Goddard, Maryland. This link is maintained continually in order to avoid the time that would be required to establish a link when a GRB trigger occurs. GCN sends a packet at one minute intervals and the LOTIS system echoes the packet back to GCN. If either system, GCN or LOTIS, detects a break in the link, the codes automatically try to re-establish the connection. When the communication link receives a GRB trigger, a Unix socket packet is sent to the telescope manager code if the coordinates are within the LOTIS field-of-regard and if the telescope is in observation mode. The manager moves the telescope mount to the GRB coordinates and sends Internet socket messages to the camera computers to begin acquiring images. All images are written to disk. The time between receiving the GRB trigger and the first image exposure is about 4 sec; the time for the mount move is the limiting factor.

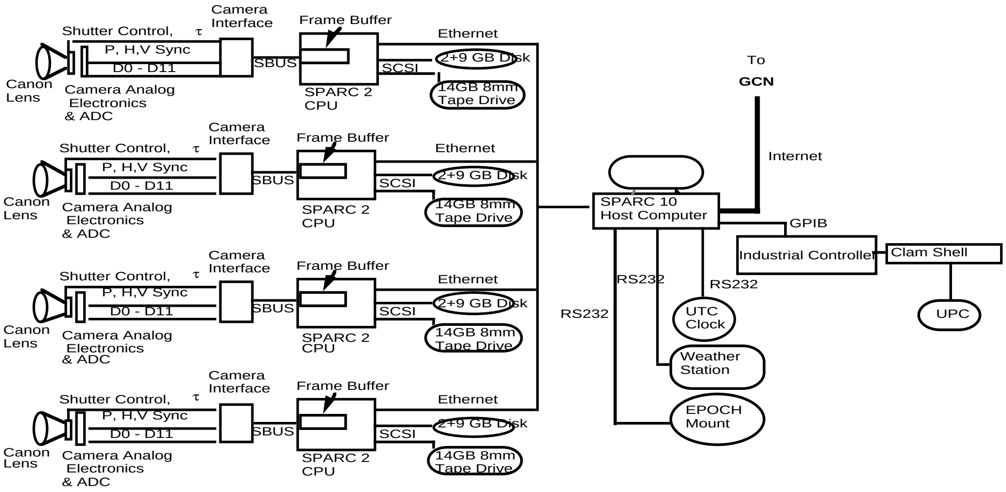

Figure 4. LOTIS data acquisition system

The on-line programs are scheduled to run at specific times each night. The host code opens the telescope housing, initializes the mount, and establishes the socket connections to the communication code and to each of the camera control codes. The camera codes purge the previous night's data, initialize the cameras and wait for commands from the host computer. While waiting for burst triggers which happens once ~20 days, survey images are taken periodically at specific positions in the sky. These are called sky patrol images and are used for baseline measurements. At regular intervals during the night, the cameras automatically adjust their offset to compensate for changing conditions. The host code monitors the weather and shuts down the telescope if rain is detected. The images and reports are written to 8 mm tape (14 Gbyte capacity) at the end of the observation.

6. LOTIS OPERATION AND PERFORMANCE

LOTIS started its operation in October 1996. Figure 5 shows a partial image of the region around M31 taken with a LOTIS camera using a 20 sec integration time. The field for this partial image is only 512 x 512 pixels (2.1 x 2.1°). In this image mV~14 objects are easily recognized. The theoretical sensitivity of the LOTIS cameras without CCD cooling is mV~13 complete magnitude (defined to be 100% detection efficiency) with 10 sec exposures. In practice, mainly due to variable weather conditions and temperature dependent focus effects we have achieved complete magnitudes of mV~11 to 12 for the interesting events we have recorded.

To date LOTIS has responded to 36 GCN/BATSE GRB triggers. Six of these triggers were recorded while the GRBs were still emitting gamma-rays. We have seen no evidence of simultaneous optical activity in the GRB error boxes down to mV~11 complete magnitude level. This limit is the lowest simultaneous optical flux limit available as of today. The results are published in References 9 and 10 as well as at http://hubcap.clemson.edu/~ggwilli/LOTIS.

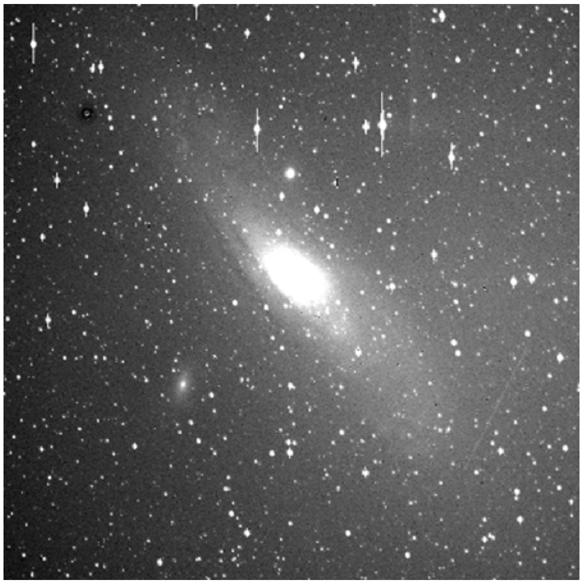

Figure 5. M31 taken with a LOTIS camera.

In addition to the optical counterpart search, we are interested in studying and classifying the brightness variations of the large number of objects in the sky patrol images. The first health of Figure 6 shows the measured intensity of a single star extracted from the sky patrol images from a single night. For fairly bright stars, we can achieve a sensitivity to brightness variations of σ_{mV} ~ 0.03 and for dim stars the sensitivity is σ_{mV} ~ 0.09 level. The sky surveys produce 2 images per field, 4 times a night. This data will be valuable for studying the variability of a large number of objects. Work is currently under way on reducing the sky patrol images to a variable star database. One example of LOTIS variable star data, GP-AND, is shown in the second panel of Figure 6. The 113 min period and the variability between mV~ 11.1 to mV ~ 10.5 of this star is clearly visible. In this plot, fluctuations due to sky background have not yet been corrected. More data analysis is in progress.

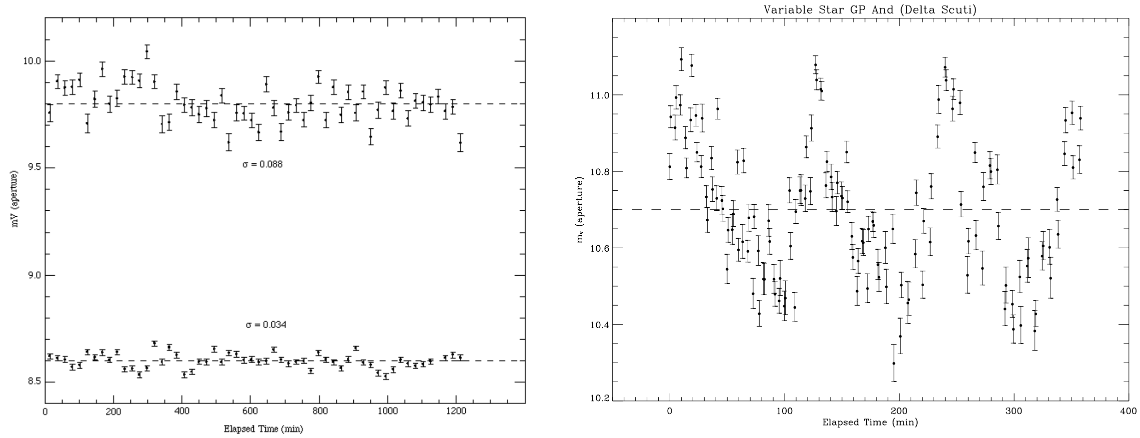

Figure 6. Example of LOTIS photometry. The first panel shows that our photometry is good to σ_{mV} = 0.1 for mV~10 objects. The second panel is a light curve measured by LOTIS for GP-AND variable star. It has 113 min period and varies between mV ~ 11.1 to 10.5.

7. SUMMARY

The LOTIS instrument is a fully automated wide-field-of-view telescope system dedicated to the search for optical counterparts of gamma ray bursts. The system is robust and has proven to be reliable through long term operation. We are currently upgrading the cameras with thermo electric cooling so that the system will be sensitive to mV~16 level; this upgraded system will be operational by spring of 1998 when the rainy season is over in California. We are also constructing a 0.6 m telescope for higher sensitivity called Super-LOTIS. This system will be sensitive to mV~19 objects at 10 sec integration time and mV~21 with 60 sec integration times. While upper limits are useful for constraining GRB models, the GRB light curves at early time will provide a crucial tool for understanding the central engine that powers GRBs.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. C. A. Meegan *et al*., Nature **355**, 143, 1992.
2. E. Costa *et al*., Nature **387**, 783, 1997.
3. L. Piro *et al*., A & A, in press, 1997.
4. T. Murakami *et al*., IAU *Circ*., 6729, 1997.
5. J. van Paradijs *et al*., Nature **386**, 686, 1997.
6. M. Metzger *et al*., IAU *Circ*., 6655, 1997.
7. S. Barthelmy *et al*., AIP Conf. Proc. **308**, Gamma-Ray Bursts, ed. G. J. Fishman, J. J. Brainerd, & K. Hurley (New York: AIP), 643, 1994.
8. H. Park *et al*., Astrophysical Journal **490**, 99, 1997.
9. H. Park *et al*., Astrophysical Journal Letters **490**, L21, 1997.
10. G. Williams *et al*., Proceedings of the 4th Huntsvilles Gamma-Ray Bursts Workshop, 1998.

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