LA-UR-97-3070

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Title: Flare Star Monitoring with a New
Photon-Counting Imaging Detector

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Flare Star Monitoring With a New Photon-Counting Imaging Detector

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). A search for faint time-varying optical signals from the nighttime sky has been conducted in parallel with the programmatic development of a new type of imaging detector. This detector combines high spatial and high temporal resolution with single-photon-counting sensitivity over a 40-mm diameter large-area format. It is called a microchannel plate with crossed delay line readout, or MCP/CDL, and is placed in the focal plane of a telescope to collect time-resolved images from objects such as flaring stars and other astrophysical transient sources. A short-lived prototype MCP/CDL was used to provide the initial stellar images for this project, but we could not generate any extended database with which to characterize flare star populations. Consequently, a supplementary experimental search for optical transients was begun, utilizing the NASA 3-meter-aperture Liquid Mirror Telescope (LMT) facility in Cloudcroft, NM.

1. Background

Several groups in the Nonproliferation and International Security (NIS) Division at the Los Alamos National Laboratory (LANL) have developed a new detector for some programmatic applications in low light level imaging and remote sensing. The detector is based on microchannel plate intensifier technology and uses a crossed delay line readout, and so is denoted as a MCP/CDL. It is the newest in a series of photon counting detectors developed over many years for space instrumentation, starting with the Fast Imaging Ranicon Experiment (FIRE) detector, and followed by the microchannel plate with wedge-and-strip readout that is currently used on the extreme ultraviolet telescopes on board the ALEXIS satellite. The MCP/CDL detector combines high spatial resolution with high temporal resolution while maintaining single-photon counting sensitivity over a large area

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(Baron and Friedhorsky, 1993). The current version of the detector has approximately 2000 x 2000 pixels over a 40-mm-diameter circular format, and can record more than 10^6 photons per second. The feature that sets the MCP/CDL technology apart from others is the capability of time-tagging photons with high temporal resolution — submicrosecond in the earlier versions of the electronics, and 100 picoseconds in the latest version. Time-tagging enables reconstruction of images collected from moving platforms and changing view angles, as well as the recording of faint optical transient effects such as we are seeking. The extremely high temporal resolution of these new readout electronics opened a new remote sensing channel with the MCP/CDL detector — that of a single-photon-counting LIDAR capability with range resolution on the order of 1 cm (Priedhorsky, Smith, and Ho, 1996).

Microchannel plate technology, photocathode deposition, and vacuum handling techniques associated with the construction of these detectors, although demanding, do not represent the state-of-the-art with respect to the MCP/CDL. Instead, it is the high-speed analog and data-acquisition digital electronics for reading out the detector at several million counts/second, and the algorithms for image reconstruction that truly represent state-of-the-art. The detector and data acquisition electronics were developed primarily by the Hydrodynamic and X-Ray Physics and Space Data Systems groups at LANL.

Data from this sensor are stored in digital format. As a result, a large part of the effort in analyzing images and displaying results resides in the development of the algorithms used to reconstruct images. Such algorithms remove apparent motions of stellar fields, remove detector nonlinearities, and permit us to search for temporal variations in astrophysical objects. Algorithm development for the MCP/CDL has been carried out primarily by Cheng Ho of LANL, who collaborated with us in this project.

One additional programmatic application of the MCP/CDL ultimately had a bearing on this project — orbital debris tracking and characterization. Searching for optical transients in stellar fields is quite similar to searching for optical tracks left by sunlight glinting from small (~ cm size) objects in low earth orbit at twilight. The MCP/CDL effort in orbital debris tracking led us to a collaboration with a NASA observatory located in Cloudcroft, NM, and this collaboration ultimately provided us with optical transient data from a 3-meter-aperture telescope, described later in this report.

2. Research Objectives

The primary research objective of this LDRD project was to apply the unique capabilities of this MCP/CDL detector to a ground-based astronomy experiment, and to demonstrate its time-resolved imaging properties. When coupled to an appropriate telescope, this detector is ideally suited to the observation of weak transient phenomena, such as the emission of flares from magnetically active red dwarf stars in our galaxy, and to the search for astrophysical phenomena such as optical counterparts to gamma-ray bursts, a topic currently of intense interest in the astrophysics community. A secondary research objective was to collect a sufficiently large number of time-resolved images of stellar fields in order to conduct a statistical analysis of the number and strength of flares from red dwarf flare stars in our galaxy. Red dwarfs comprise approximately one fourth of the population of stars in the galaxy, and during a portion of their lifetimes pass through a flaring stage (Mirzoyan, 1990). Most of the detailed studies of flare stars done in the past have been confined to a few well-known and well-characterized stars and star clusters. A secondary goal of this project was to provide a study of flaring in the more general population of red dwarfs.

3. Importance to LANL's Science and Technology Base and National R&D Needs

The use of this programmatically-funded and developed MCP/CDL detector for the science of the flare star and optical transient LDRD project represents a commitment by Los Alamos National Laboratory to a continuing and strong scientific base. The MCP/CDL is a state-of-the-art technology, and our efforts with it help to maintain the Laboratory's credibility in imaging technology. The detector has potentially many useful applications in remote sensing under low-light level conditions, such as non-proliferation monitoring, orbital debris tracking, and defense-related areas. A successful demonstration of imaging astrophysical objects from this project contributes a major step towards the advertisement of the Laboratory's capabilities to an entirely different professional audience.

4. Scientific Approach

Our scientific approach to demonstration of the MCP/CDL in characterizing flaring

from low-luminosity red dwarf stars was one of choosing the appropriate spectral regions that optimize the signal-to-noise ratios, and then to assemble all of the experimental tools necessary to carry out those observations. In the case of the red dwarf stars, the most appropriate region in which to collect data is in the ultraviolet, where the detector quantum efficiency is the highest, and the greatest contrast is provided between the quiescent optical background and the flares. U-band photometry over the range of 3300 Å to 4000 Å, where the diffuse sky background is low but the atmospheric transmission is acceptable, is a reasonable choice (O'Connell, 1987). Other useful spectral bands are B-band, centered at 4400 Å, and V-band, centered at 5500 Å, which were used in data collection with the CCD detector of the 3-meter-aperture telescope in Cloudcroft.

5. Accomplishments

Our opportunities to utilize the MCP/CDL for this project were closely tied to the programmatic development schedule and to the low-light-level imaging demonstrations of the detector. These demonstrations were conducted at dark, remote sites under starlight-only conditions with the host of computers and peripheral equipment necessary to operate the detector. Three of these field tests were conducted at the Laboratory's TA-33 site in December of 1993, February of 1994, and July of 1994. In addition, a one-day field trip was made to the Fenton Hill Laboratory site in April of 1995. During each of these tests the detector was coupled to a telescope and stellar images were collected, with the (digital) data stored on portable disks for later analysis. Several examples of these images are shown in Figures 1–3.

The first example of a visible image integrated over 400 seconds, and taken with a 15-cm-diameter refractor telescope, is shown in Figure 1. This stellar field is near open cluster NGC7243, and the apparent motion of the stars in this image has been removed in software. The two remaining streaks are fixed hot spots on the surface of the detector which become tracks after the stellar images are restored. The faintest star in the image is at a visual magnitude of 12.5. Image reconstruction was provided by Cheng Ho.

The second sample, an ultraviolet image taken with the U-band filter and the modified 17-cm-aperture Questar telescope, was observed in the vicinity of the constellation Aquila, and is shown in Figure 2. In Figure 3, an example of the time history of uv photons (not a flare event, however) emitted from one of the brighter stars of Figure 2 is shown. This time history curve includes the effects of spatial variations due to

gain nonuniformities over the surface of the detector — effects which can be removed in post-processing software.

We should note that the examples of reconstructed images shown here were taken with a sealed MCP/CDL detector that had a degraded quantum efficiency in the visible and ultraviolet, as well as some moderately reduced spatial resolution. These images do not represent the best that the detector can generate. The detector pixel size for these images was approximately 70 microns, compared to the demonstrated < 20 micron value measured with a prototype MCP/CDL in the laboratory. In spite of this, we were encouraged by the initial results, and anticipated that a fully operational detector would generate the high quality images we sought.

During the course of this project several MCP/CDL detectors were constructed. Only one of them remained operational for any significant length of time, while the others suffered various photocathode, high voltage, and vacuum failures.

Also over the course of the project, a large amount of equipment necessary for collecting astronomical data was established. This included several telescopes and mounts, ranging from a 15-cm-aperture refractor system, to a modified 17-cm-aperture Questar telescope, and finally to a custom-designed 30-cm-aperture Ritchey-Chretien optical design telescope. This latter telescope was designed to operate over a spectral range from the ultraviolet through the visible, and to provide a flat-field, nearly diffraction-limited image over the 40-mm-diameter image plane that matches the microchannel plate physical dimensions. Funding for this instrument was provided through an FY 1994 LDRD capital allocation. Delivery of the completed telescope took place in February of 1995. A programmable azimuth-elevation mount for the Ritchey-Chretien telescope was constructed from a shipboard radar mount, and used for the April 1995 field test.

6. International Astronomical Union Colloquium #151

The principal investigator represented the MCP/CDL development project and its application to flare star measurements at the International Astronomical Union Colloquium #151 on Flares and Flashes in Sonneberg, Germany, in December of 1994. The status of the project, and the unique capabilities of the sensor were presented as a contributed paper, and it was published in the Proceedings of the conference (D.E. Casperson et al., 1995).

At this IAU Colloquium we took advantage of the opportunity to meet with the major players in the astronomy and astrophysics community who are interested in

recording and characterizing optical transient events. In addition to conducting all-sky optical monitoring and flare observations, this community is extremely interested in identifying potential optical counterparts to gamma-ray bursters, or GRBs. GRBs are astrophysical objects that emit bursts of x rays and gamma rays lasting typically tens of seconds. The source of GRBs is not yet understood — it is not even known if these objects are confined to our own galaxy, or whether they are extra-galactic in origin, even after several decades of observation. They are seen quite regularly by satellites with x-ray detectors. But no simultaneous optical emission has ever been identified with GRBs, and such identification would constitute a major step towards identifying their source. It is clear that a fully operational MCP/CDL detector with its extremely high sensitivity could play a major role in searching for these optical counterparts, particularly if it were part of a robotic system that could respond quickly to a triggering x-ray event from the satellites.

7. The Liquid Mirror Telescope

When it became evident that a long-lived, fully operational MCP/CDL detector with a high quantum efficiency photocathode would not become available in a timely manner to generate extended data sets of stellar images for this project, we chose to follow a supplementary course of action. At the beginning of FY 1996 we made contact with the team at the Liquid Mirror Telescope (LMT) facility in Cloudcroft, NM, with a request for some observing time on their 3-meter-aperture rotating-mercury-mirror instrument.

It was through the orbital debris tracking effort that we became acquainted with this team at the LMT. The Cloudcroft facility is tasked by NASA to characterize low earth orbit debris that passes within their field of view, over their upward-looking telescope and CCD detector package. The LMT facility manager (also an astronomer) is Mark Mulrooney of Lockheed-Martin, who supports astronomy projects during those hours when debris data cannot be collected. Our collaboration with them resulted in three trips to the LMT in 1996. They have kindly supported us in FY 1996 (and continue to do so in FY 1997) in our search for weak optical transient events. We have generated a database of stellar images for us to carry out a statistically meaningful search for flares.

The imaging technique by which the LMT collects data from its rotating mercury mirror telescope and fixed CCD camera is called time delay and integration, or TDI mode. In this mode, pixels in the CCD chip are continuously collecting photons from starlight. The rows of pixels are oriented such that the image-generated charge is transferred from

row to row (via the normal CCD readout process) synchronously with the motion of the sky image across the detector face. The output is a continuous image of the sky, where the integrated exposure time for any given star equals the image transit time across all the rows of the CCD. In the case of the Cloudcroft LMT, this integration time is 96 seconds, which under good seeing conditions results in a limiting stellar magnitude of $m_V = 22$. One example of a TDI image from Cloudcroft that includes a barred spiral galaxy is shown in Figure 4.

In order for us to use the LMT for time-resolved measurements that we seek, we use a variation of the TDI mode. The CCD chip is now rotated slightly, so that the 96-second integration is uniformly distributed across 100 pixels, and the output image becomes a transverse star "trail" with approximately one second temporal resolution. The limiting magnitude is now reduced relative to the normal TDI mode by the fact that photons from a star are spread out over multiple pixels while the density of background photons remains fixed. Even with this reduction, the LMT is capable of looking for temporal variations on stars that are recorded down to approximately $m_V = 17$. A sample image of a 100-pixel star trail from the LMT is shown in Figure 5. The current database of stellar images represents approximately twenty hours of observation at the LMT.

8. Future Efforts

As a direct result of our ongoing collaboration with the Cloudcroft LMT, we have been invited to visit and collect data from a 5-meter-aperture LMT facility presently under construction at the University of British Columbia near Vancouver. Paul Hickson, a professor at UBC who wrote the data collection and analysis software for the Cloudcroft LMT, is leading the effort and has extended an invitation for us to search for optical transients when construction is completed, perhaps as early as 1998. Such future efforts would be a direct result of having participated in this LDRD project.

With respect to the future of the MCP/CDL, a new contractor for building detectors and depositing photocathodes has been chosen, and a new operating tube is expected in early FY 1997. The written test plans for collecting images with the new detector include our astronomical observations, so that we will have a chance to show the ultimate capabilities of this unique sensor.

It is worth noting that the search for optical transient events has become a high priority activity throughout the astrophysics and astronomy community. The Fenton Hill site has been chosen for locating the Los Alamos MILAGRO project, a high energy cosmic

ray telescope. Along with MILAGRO, several groups are now in the process of implementing robotically operated telescopes with CCD cameras for searching out transient events, such as MILAGRO cosmic ray optical counterparts, supernovas, and optical counterparts associated with gamma ray bursts. The expertise and much of the equipment that was generated from this LDRD project will very likely become an integral part of this growing Fenton Hill Observatory.

Publication

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Fig. 1. Visible image of a stellar field near the Open Cluster NGC7243. This image was obtained with the MCP/CDL detector and refractor telescope by integrating photons over a 400 second interval from a fixed telescope position. Apparent stellar motion from the Earth's rotation has been removed in software, generating two streaks from fixed detector hot spots in the final image.

Fig. 2. A 400-second ultraviolet (U-band) image of a stellar field near the constellation Aquila, taken with the MCP/CDL detector and a 7-inch aperture Questar telescope in a fixed position. Apparent stellar motion from the Earth's rotation has been removed in software.

Fig. 3. Sample of the time history of U-band photon emission (not a flare event) from one of the brighter stars in the image shown in Fig. 2. Most of the observed temporal variation is due to gain nonuniformity over the surface of the detector that has not yet been removed in software

Fig. 4. Sample image of a barred spiral galaxy from the 3-meter-aperture Liquid Mirror Telescope (LMT) facility located in Cloudcroft, NM. This CCD camera image, courtesy of Mark Mulrooney (NASA/JSC), was obtained with the time-delay and integration (TDI or "drift-scan") method and represents 96 seconds of total exposure. The stellar magnitude limit utilizing this technique at the LMT is approximately $m=22$.

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Fig. 5. Raw CCD image of stellar time-history tracks generated at the LMT using a variant of the time delay integration (TDI) technique. For this image, the CCD sensor is rotated slightly relative to its position for the data of Fig. 4. The 96-second integration is displayed over 100 pixels, providing one-second temporal resolution over each track.