ASTRONOMY FROM WIDE-FIELD IMAGING

Part Two:

DIGITAL DETECTORS IN WIDE-FIELD IMAGING

THE CCD ARRAY CAMERA FOR THE MACHO PROJECT

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ABSTRACT. We have developed an astronomical imaging system tailored to our search for gravitational microlensing by compact objects in the halo and disk of the Galaxy. The challenge of detecting rare microlensing events is to monitor ~ 10 million stars per night and distinguish genuine events from other sources of variability. The Large Magellanic Cloud and the Galactic bulge provide the high surface density of resolvable stars necessary for this task. A dedicated 50 inch telescope at Mt. Stromlo Observatory has been producing science data since the fall of 1992. Our system incorporates eight 2048 x 2048 CCDs into two focal planes for simultaneous imaging in two passbands (4500-6300 and 6300-8100 Å). Each focal plane consists of four 'edge-buttable' CCDs in a custom mounted 2 x 2 array. The 0.62 arcsecond pixel scale (15 μm) yields a 40 x 40 arcminute square field of view in each frame. A sophisticated point spread fitting photometry package extracts up to 600,000 useful magnitudes per color per frame. The data collection rate we need is obtained by simultaneously reading out all sixteen CCD outputs (two per chip) at 34 KHz with 16 bit digitization. With exposure times of 150-300 seconds and a 70 second readout time we can collect up to 100 fields per night. These rates are designed to allow us to detect or rule out massive compact halo objects (MACHOs) in the 10^{-6} - 10^{1} $M_{\odot}$ range.

The evidence for large quantities of unseen matter surrounding normal galaxies, including our own, is widely accepted. However, the nature of this dark matter is still completely unknown. Exotic particles such as axions, massive neutrinos, or other weakly interacting massive particles (WIMPs) have been proposed (Primack et al. 1988; Kolb & Turner 1990). An alternate possibility lies in ordinary matter. While it cannot be in readily detectable forms such as gas,

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dust or stars, it could exist in the form of massive compact halo objects (MACHOs). These could be brown dwarfs or 'Jupiters', neutron stars, old white dwarfs, or black holes. Paczynski (1986) suggested that such objects could be detected by searching for gravitational microlensing of stars. As a MACHO passes across the line of sight to a distant star the apparent brightness would temporarily increase in an identifiable fashion. These events are expected to be very rare. For stars in the LMC typical Galactic halo models imply that only one star in two million would be microlensed at a given time. The MACHO project (Alcock et al. 1992; Bennett et al. 1993) is carrying out such a search and intends to confirm or rule out the existence of halo dark matter in the form of MACHOs for a mass range $10^{-6}\ M_\odot$ to $10\ M_\odot$.

To separate microlensing from other intrinsic sources of stellar variability one can use the characteristics expected for a population of microlensing events:

1) events are non-repeating;
2) light curves are symmetric in time;
3) the amplification is achromatic;
4) the shape of the light curve is known;
5) the relative frequency of different amplifications follows a known distribution;
6) the distribution of a set of microlensed stars in the CM diagram should not differ from that of the overall population.

The duration of these events is expected to be ~ $100\ \sqrt{(M/M_\odot)}$ days where M is the mass of the MACHO. Hence the time scale of hours to months covers a mass range from $10^{-5}\ M_\odot$ to $10\ M_\odot$.

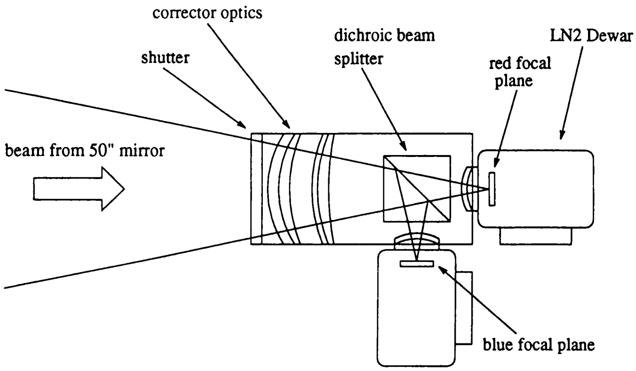
Our project goals translated to a hardware/system scheme for generating nightly photometric measurements of close to 10 million stars for at least a four year period. Some features of the system are:

1) simultaneous imaging in two passbands;
2) wide field-of-view;
3) high optical efficiency;
4) low dead time;
5) dedicated telescope;
6) fast crowded field photometry.

The imaging system is mounted at the prime focus of the 1.27 m telescope at Mt. Stromlo Observatory. This telescope has been completely refurbished for this project. A three element corrector and a dichroic beam splitter are combined to simultaneously image in two passbands with a 1 degree diameter corrected field-of-view (Fig. 1). The passbands were chosen to reject a minimum of the available light while attempting to match the signal sensitivity in the two colors. Our 'red' passband spans 6300-8100 Å and our 'blue' covers 4500-6300 Å.

Each of the two identical cameras uses a 2 x 2 array of Loral/Ford 2 side 'edge-buttable' 2048 x 2048 CCDs. The thick frontside illuminated 15 µm x 15 µm pixels are operated in the MPP mode at 165K and cover approximately 0.62 arcseconds on the sky to yield a 0.5 square degree (40" x 40") field. Our custom kovar focal plane support consists of four quadrants which lock onto a lower plate for a rigid and flat mounting. This design allows for replaceable quadrants, temperature control from the lower plate and optical coplanarity to 20 µm for joint focus in the two colors. No attempt was made to align rows or columns across the ~ 600 µm gap between the CCDs.

We utilize a single controller to run all eight CCDs (Fig. 2). It has a DSP chip which generates the timing signals for the CCDs and the 16 bit A/D converters. The timing parameters are downloaded to the DSP from a microcontroller chip on the board which runs the FORTH language. This chip serves as the interface to the user for camera commands and allows for



1.27m parabolic mirror f/4.47
reimaged to f/3.88 by
3 element corrector
Dichroic Beam Splitter and Filters yield
passbands:

macho_blue 4500 -6300 A
macho_red 6300 - 8100 A

Figure 1. Optical path to focal planes.

programming of the camera control parameters. The controller and the A/D converters were purchased from Advanced Technologies/Photometrics of Tucson, AZ. Opto-isolation and careful attention to grounding issues were applied to ensure that the red and blue cameras were isolated from the telescope and from each other. The eight 16 bit serial data streams from a single camera are combined into a single 8 bit data stream (1 bit per channel) and transferred to the control room over an optical fiber. The data is 'descrambled' before being written into dual-ported vme memory.

The system performance meets our design specification for the experiment but points out the differences between optimum bench top specs and real world '16 channels on the telescope' conditions. Under routine observing conditions, the readout noise is 6 - 10 e^- for our 70 second readout of the array (including 100 pixel overscan). This level of noise is very acceptable because our lowest sky level is ~ $3000e^-$. A serious problem that we did not discover in low contrast lab testing is crosstalk between the channels within each camera. No crosstalk occurs between the separate cameras. In particular, a bright source on one channel can induce a response on a second channel generating extra peaks or holes in an image. Fortunately the effect is linear, stable in time, and typically at the 4 parts in 10,000 level. As a result we have calibrated the effect and include corrections for it as part of our flatfielding process. Currently we archive raw data and run the correction process before doing the photometry. We will soon implement the use of a Sunsparc 10/51 to flatten and correct the data during the transfer from dual-ported memory to disk without decreasing the throughput of the system.

In addition to crosstalk there have been some other interesting problems with the CCDs. We initially had much higher noise and pickup problems. We found that changing the LDD output FET drain voltage from the suggested value of 19 volts to 24.5 put the transistor in a more stable, higher gain regime. Our initial images had striping due to vertical mixing of pixels as they were being transferred from the imaging array to the horizontal readout register. This appears to have been caused by the lack of an MPP implant under the array transfer gate structure. To get around this, we adjusted our voltages so that the imaging array gates run at -9.5/+2.0 V and the array transfer gate runs at -5.0/+2.0 V. This effectively dumps the first row of the array into the horizontal register. A similar situation occurs at the top of the array where a 'fast clear' structure forms the boundary of the imaging area. This reduces the imaging area of the array to 2046 x 2048. Even with the individual CCDs working properly we still have to contend with the

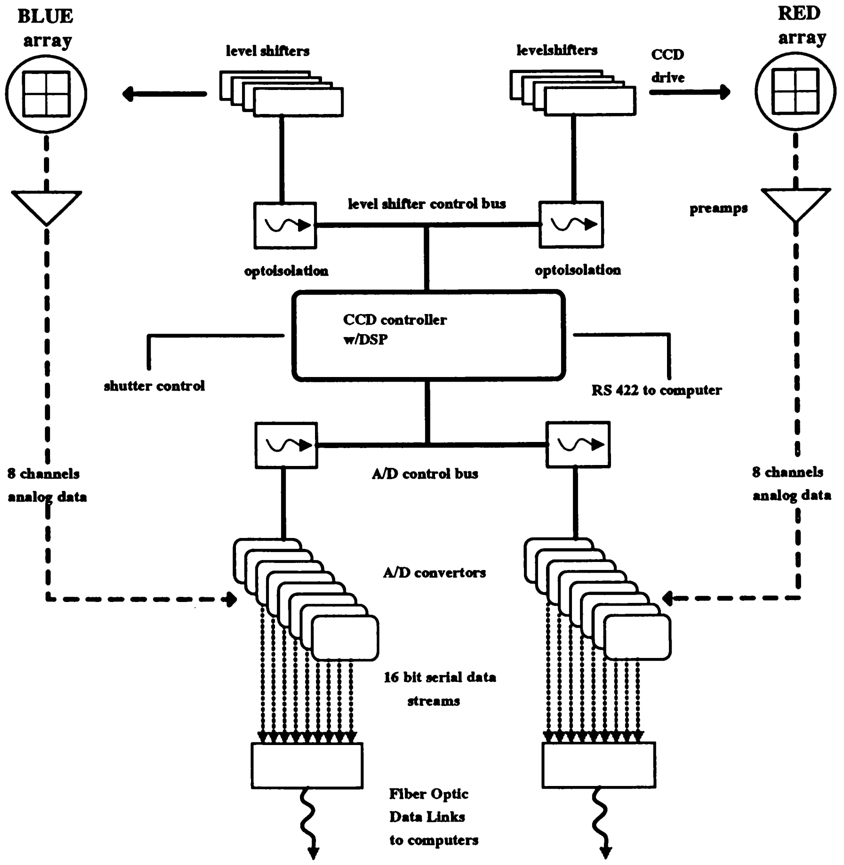


Figure 2. Camera architecture.

fact that different CCDs will have different quantum efficiencies (primarily in the blue). Our focal planes were populated from three separate chip fabrication runs, hence this effect is not too surprising (in hindsight!). Since the telescope has a 'Modified German Mount' we can observe the same location on the sky from either side of the mount axis. These two configurations differ in that the tube of the telescope (and hence the focal plane) is rotated by 180°. This means we routinely image stars in different CCDs on different observations depending on which side of the mount axis the telescope tube lies. As a result we have to make corrections to the data to account for the *QE* offsets between different CCDs. Fortunately we have large numbers of stars and observations with which to calibrate this effect.

Our image reduction is carried out by a crowded field photometry package called Sodophot which is derived from Dophot. A template containing magnitudes and positions from a 'best' image is used as input for routine reductions. Various output flags are included for crowding, bad pixels, goodness of fit, etc. The output is then gathered to form a time series. This method is quite fast and is designed to keep up with as many as 10 million stars per day on our 4 processor Solbourne computer.

The current system status has the cameras, telescope, and data archiving operating routinely. We have taken over 12,000 dual color images as of September 1, 1993. An automated photometry-to-database system will be implemented in the future. Until then the photometry will be performed offline in the US and Australia. An offline database with about 3 million stars for about 250 epochs has been constructed and our first science results are based on that offline data set (Alcock et al. 1993). The time series analysis of these stars has discovered thousands of cepheids, RR Lyraes, eclipsing binaries, and LPVs in the bar of the LMC (Cook et al. 1993). By combining our 'catalog' of variables in the LMC with follow-up observations we expect to obtain many interesting results.

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