ULTRACAM – studying astrophysics on the fastest timescales

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Abstract

The history of observational astronomy has shown that major advances in the science almost always result when a new area of observational parameter space, such as wavelength coverage, angular resolution, sensitivity or sky coverage, becomes accessible for exploration. ULTRACAM is an ultra-fast, triple-beam CCD camera which has been designed to study one of the few remaining unexplored regions of observational parameter space – high temporal resolution. The camera, which has recently been funded in full (£292k) by PPARC, will see first light during the summer of 2001 and will be used on the 4.2-m WHT, 2.5-m INT, 2.0-m Liverpool Telescope, 3.9-m AAT, 9.1-m SALT and the 1.9-m SAAO Radcliffe Telescope to study astrophysics on the fastest timescales.

Key words: Ultracam; time resolution; photometry

1 Introduction

When the ING decided to make the JKT a single-instrument telescope in 1996 in order to reduce running costs, UK astronomers lost access to the last of their research-class photoelectric photometers (the Peoples' Photometer and the MPF) and hence lost their capability to do high-speed, multi-waveband optical photometry. For all of the advantages of the CCD cameras which replaced these instruments, they have never been able to match the speed of photoelectric photometers. The situation has now changed, however, with the advent of low-noise, high quantum-efficiency, large-format frame-transfer CCDs and associated advances in the data acquisition, data reduction and data storage hardware. ULTRACAM will exploit these technological developments, imaging fields of up to 10 arcminutes with essentially no dead-time (even at kHz frame rates) simultaneously in three different colours. This will give back to UK astronomers a long-awaited and far-enhanced capability to do high-speed, multi-wavelength optical photometry.

2 Science drivers

The fastest timescale variations likely to be observed in an astrophysical environment are milliseconds (corresponding to the innermost orbits around neutron stars and black holes). Variations of faint sources on timescales longer than a few seconds have already been explored by conventional CCD instruments. ULTRACAM has been designed to explore the region of observational parameter space which lies between these two extremes, namely photometry of faint objects on timescales of seconds to milliseconds.

The resulting list of scientific applications of ULTRACAM is vast. On timescales of milliseconds, we will be able to study the optical emission from pulsars and search for the optical analogue of the kilohertz quasi-periodic oscillations (QPO's) found in X-ray binary stars. On timescales of a hundredth of a second, we will be able to perform non-redundant-mask (and speckle) imaging of nearby giant stars. On timescales of a tenth of a second, echo mapping experiments become possible, enabling the geometries of cataclysmic variable and X-ray binary stars to be determined. On timescales of a second, we can measure the sharp ingress and egress of the eclipse of a white dwarf in a close binary star, thereby determining its mass and radius for comparison with theory. The list goes on, so we will restrict the remainder of our discussion in this section to the description of one of the key scientific projects we hope to perform with ULTRACAM – eclipse mapping of accretion discs.

Accretion discs are pivotal in the transport of angular momentum in a wide variety of astrophysical objects. It is through them that protostars grow and the compact objects at the heart of many X-ray sources can be fuelled. Much of what we know about these discs has been learnt using the eclipse mapping technique developed by Keith Horne, where the shape of the light curve in eclipsing close binaries is used to map the brightnesses and temperatures over the disc. Relatively few systems, however, are bright enough for this technique to be applied. This is particularly true of dwarf and X-ray novae in their low states. For the past few years, about one new X-ray nova, many of which harbour black-holes, has been discovered each year. It can only be a matter of time before a deeply eclipsing system is discovered, giving us the chance to see where in the system the optical light comes from in quiescence (the standard disc model and the more recent advective solutions differ sharply on this). It is a sobering thought that if such a system were to be discovered, the UK would not have access to any photometer that could obtain competitive data on it. The two essential requirements for such work are short exposures, of order a

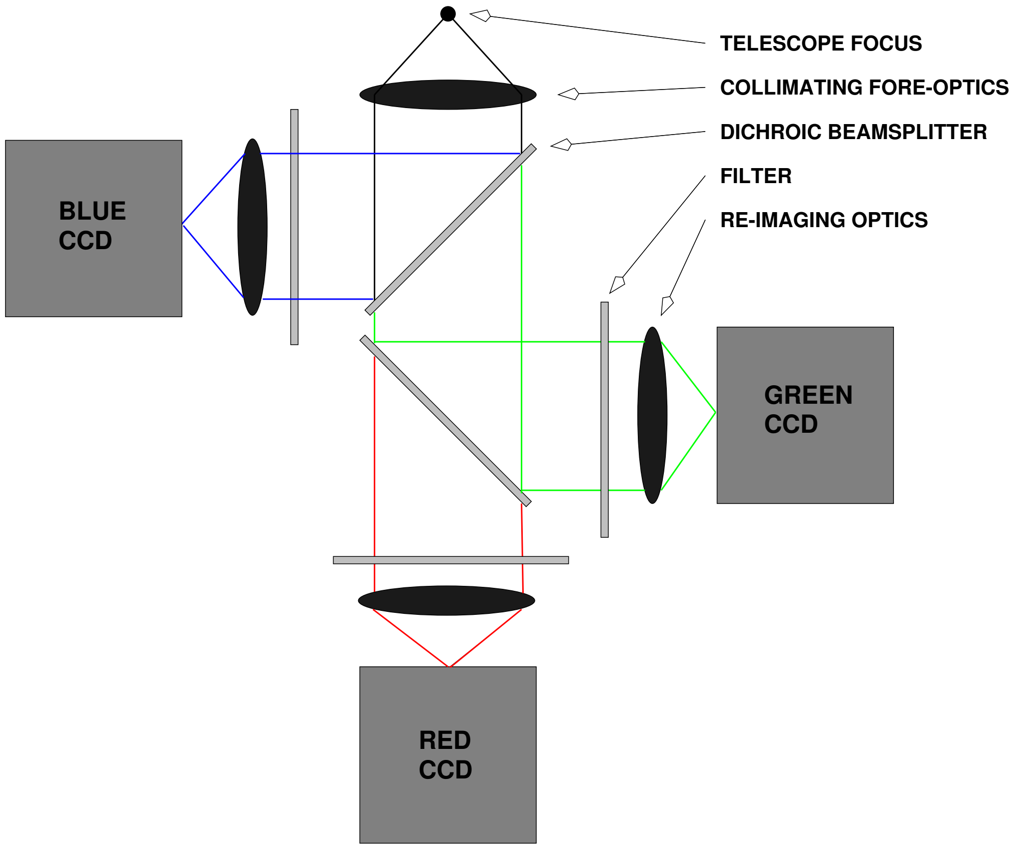

Fig. 1. Schematic representation of ULTRACAM.

second at most, and multi-band data (3 or more) in order to distinguish one type of spectrum from another (i.e. with only 2 bands you cannot distinguish a blackbody from a star; with 3 bands you can). Simultaneously recording the 3 bands is vital because accreting systems display erratic flickering which cannot be reliably disentangled from colour variations in sequentially acquired data.

3 Opto-mechanical design

The proposed optical layout of ULTRACAM is shown in figure 1. The collimating fore-optics will collimate the light from the telescope. This will be an interchangeable lens unit which will enable ULTRACAM to work on telescopes of different focal ratio. Such a scheme will also allow a variety of different pixel scales to be produced, depending on the scientific requirements of the project. The light is split into blue, green and red wavelengths by two dichroic beamsplitters and then passes through a filter. We have chosen to use the *ugriz* filter system defined by the Sloan Digital Sky Survey (SDSS), for three reasons. First, the *ugriz* system is likely to become the dominant photometric system of the future. Second, the overlaps between the *ugriz* bandpasses are minimal compared to the overlaps in the $UBVRIZ$ filter-set, which will minimize the problems associated with using dichroics to split the light between the filters. Third, the SDSS r filter has a curtailed red wing compared to the Cousins R filter, which means that fringing with the thinned chips will be non-existent in r. On passing through the filters, the light is re-focussed onto the CCD chip using re-imaging optics positioned in front of the detectors.

All of the optics will be interchangeable by hand, i.e. there are no moving parts in ULTRACAM, which simplifies the design (and reduces the cost) considerably. A single opto-mechanical chassis will house all of the optics and will provide mounting points for the 3 CCD heads. An interchangeable flange at the collimator end will enable attachment to a variety of Cassegrain turntables. Note that mechanical flexure is not of great concern as ULTRACAM is primarily an imaging photometer. The above design ensures that ULTRACAM will be a simple, compact, lightweight and hence portable instrument.

4 Data acquisition system

Figure 2 shows the principal components of the ULTRACAM data acquisition system. We will use three liquid nitrogen-cooled, back-illuminated, thinned, EEV 47-20 frame-transfer CCD chips as the detectors for ULTRACAM. The use of frame transfer chips is essential, as it provides a means of taking data in the imaging area whilst data in the masked area is being read out. As long as the exposure time is longer than the time it takes to read the data, the dead-time is essentially zero. Hence, for small windows it is possible to take 0.001 s exposures with negligible (0.0001 s) dead-time, thereby meeting the specifications outlined in section 2. Even full-frame images can be read out with millisecond dead-times as long as the exposure times are no shorter than $\sim$1 s.

The EEV 47-20 chips have imaging areas of 1024$\times$1024 pixels (each of 13 μm). Such a large chip format gives a high probability of finding comparison stars which are brighter than our target stars. This is an essential pre-requisite for accurate differential photometry. Assuming a pixel size of 0.35 arcseconds/pixel and observing at a galactic latitude of 30° (approximately equal to the all-sky average), the EEV 47-20 provides us with a 90% probability of finding a comparison star of magnitude $R = 12$, which is far brighter than virtually all of our intended target stars.

The ULTRACAM chips will be coated by EEV with their *enhanced broad-band coating*, resulting in quantum efficiencies of between 40–95% in the *ugriz* bandpasses. The readout noise of the detector is approximately 4.5 e^- at readout rates of 3 μs/pixel and the dark current is only 2 e^-/pixel/hr.

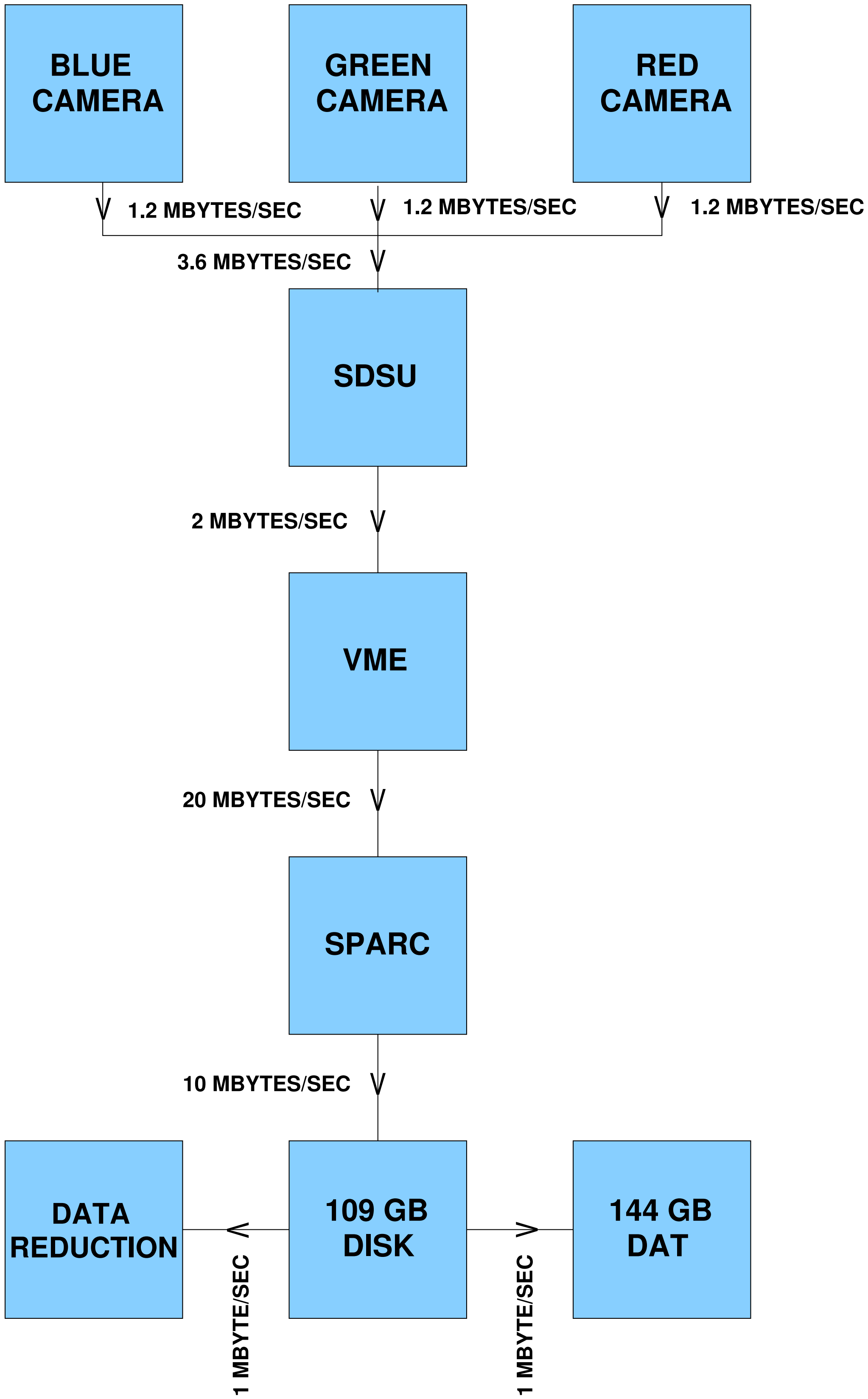

Fig. 2. Data acquisition system.

The CCDs will be controlled by a San Diego State University (SDSU) controller, provided by Bob Leach. Using a GPS receiver connected to the SDSU controller, we will time-stamp all exposures with ULTRACAM to an absolute accuracy of better than 0.1 milliseconds. The data will then be transferred from the SDSU controller to a Sparcstation. To overcome the problems of using unix as a real-time operating system, some form of data buffering is essential in order to maintain the highest data rates. This will be provided by a VME system.

Figure 2 also shows the maximum data-flow permissible by each component of the ULTRACAM data acquisition system. It can be seen that a bottleneck occurs at the SDSU controller, which can pass no more than 2 Mbytes/s of data. This sets the maximum data rate of ULTRACAM and implies that in the course of a 10-hour night, we could accumulate as much as 72 Gbytes of data. Such vast quantities of data demand two things – disk space sufficient to store at least one nights data and an archiving medium with sufficient capacity and speed to backup at least one nights data before the next night begins. The user-end of the data acquisition system will therefore consist of a SUN Sparcstation Ultra 10, running at 333 MHz with 512 Mbytes of memory, 109 Gigabytes of hard disk space (using a SUN Multipac composed of six 18 Gbyte discs) and a SUN Autoloading DDS3 DAT drive (which can archive up to 144 Gbytes of data on 6 DAT tapes). With this in place, it will be possible to observe for a whole night at the highest data rates without stopping and then archive the data at the end of the night.

Without some form of pipeline reduction, it will simply not be feasible to reduce the terrabytes of data produced in a typical observing run with ULTRACAM. Such a pipeline data reduction system will also allow an immediate assessment of the data, essential for the study of variable objects. We have simulated the performance of a pipeline data reduction system for ULTRACAM and we find that, using the Sparcstation specified above, it will indeed be possible to reduce ULTRACAM data at the same rate as it is taken, thereby allowing us to build up light curves in real time.

5 Limiting magnitudes

In figure 3 we show the limiting magnitudes for a detection with ULTRACAM (at a signal-to-noise of 10) as a function of exposure time at the GHRIL focus of the 4.2-m WHT. Each panel corresponds to a different bandpass – U, B, V, R, I and Z. In each panel there are 6 curves. The solid curves are for ULTRACAM, with the upper curve representing dark time and the lower curve bright time. The dotted curves are also for ULTRACAM, but using on-chip binning of 3×3 pixels (giving 1.05 arcsecond pixels). The dashed curves are

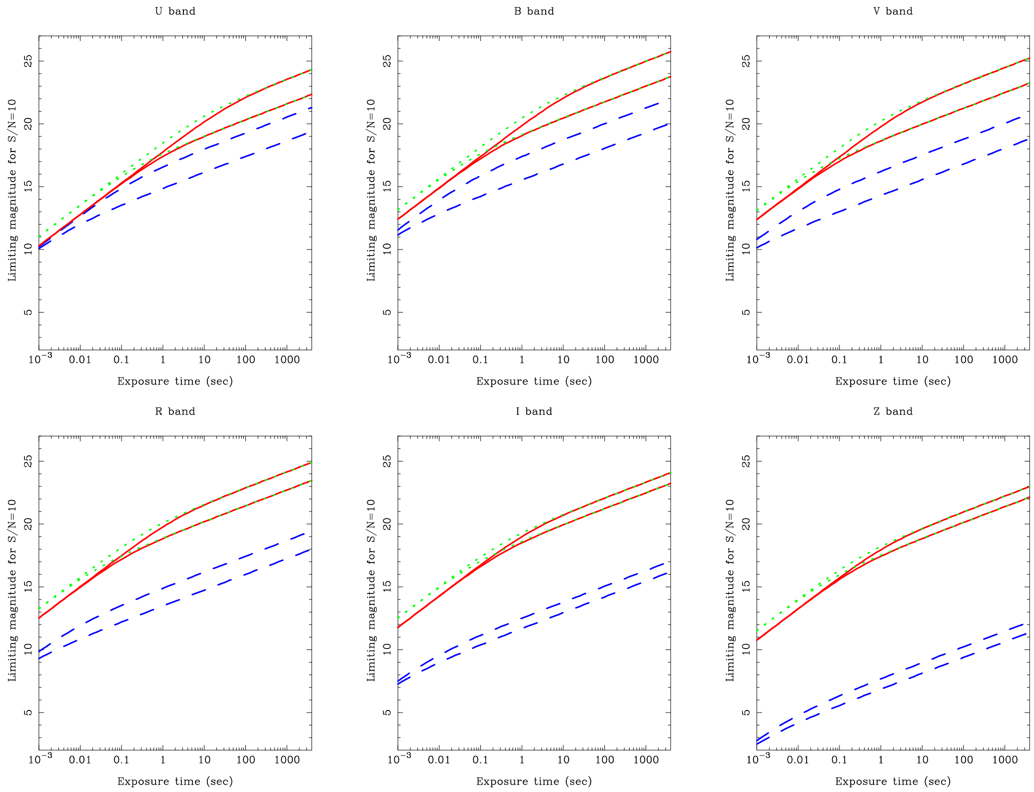

Fig. 3. Limiting magnitudes of ULTRACAM on the 4.2-m WHT.

for a photoelectric photometer, again with the upper curve representing dark time and the lower curve bright time. Changing the telescope aperture from 4.2-m to 8-m results in an upward displacement of the curves by ∼1 magnitude. Similarly, changing the telescope aperture to 2-m results in a downward displacement by ∼1 magnitude. When calculating the limiting magnitudes we have used, wherever possible, the parameters (e.g. sky brightness, extinction) given by the `signal` program written by Chris Benn for the ING telescopes. For all other parameters (e.g. detector noise and quantum efficiency, seeing, throughput of the telescope and ULTRACAM optics) we have been careful to adopt realistic values so as to accurately reflect the expected performance of ULTRACAM.

For further information, please consult the ULTRACAM web-site[1]

[1] http://www.shef.ac.uk/∼phys/people/vdhillon/ultracam