HIGH TIME-RESOLUTION ASTROPHYSICS

OPTICAL INSTRUMENTATION

Vik Dhillon (Sheffield/IAC)
OVERVIEW

**Lecture 1: ULTRACAM**
- High time-resolution astrophysics (HTRA) - what is it and why study it?
- The detection of light - an introduction to CCDs
- Instrumentation for high-speed photometry I: ULTRACAM
- ULTRACAM: science highlights

**Lecture 2: ULTRASPEC**
- High-speed spectroscopy
- An introduction to EMCCDs
- Instrumentation for high-speed spectroscopy: ULTRASPEC on the NTT
- Instrumentation for high-speed photometry II: ULTRASPEC on the TNT

**Lecture 3: HiPERCAM**
- How can we improve ULTRACAM and what would this enable us to do?
- Eliminating atmospheric scintillation noise: Conjugate-plane photometry
- Instrumentation for high-speed photometry III: HiPERCAM

**Lecture 4: Data Reduction**
- Demonstration of photometric data reduction using the ULTRACAM pipeline
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THE EVER-CHANGING SKY

- The Ancient Greeks believed celestial objects were perfect and unchanging.
We now know that all objects in the Universe vary in brightness on timescales ranging from milliseconds to billions of years.
Although astronomy has made great strides in recent decades, the study of the most rapidly varying phenomena has been largely ignored (at least in the optical!).
The advent of big telescopes and new detector technologies has now made it possible to study astrophysics on the fastest timescales (milliseconds to seconds).

Why bother? Because, it enables the study of compact objects.
In the absence of any pressure, the time taken for a test particle released at the surface of a star to fall to the centre:

- For the Sun, $M = 2 \times 10^{30}$ kg, $R = 7 \times 10^5$ km \[ t_{\text{dyn}} \sim 2000 \text{ s} \]
- For white dwarfs, $M \sim 1 \, M_{\text{Sun}}$, $R \sim 0.01 \, R_{\text{Sun}}$ \[ t_{\text{dyn}} \sim 2 \text{ s} \]
- For neutron stars and black holes, $M \sim 3 \, M_{\text{Sun}}$, $R \sim 10^{-5} \, R_{\text{Sun}}$ \[ t_{\text{dyn}} \sim 0.1 \text{ ms} \]

DYNAMICAL TIMESCALE
WHY BOTHER?

- **White dwarfs, neutron stars and black holes** are the dead remnants of stars, providing a fossil record of stellar evolution.

- White dwarfs, neutron stars and black holes are extreme cosmic environments, allowing us to test theories of fundamental physics to the limits of their predictive powers.

- White dwarfs, neutron stars and black holes in binaries, provide us with some of the most exotic and scientifically valuable inhabitants of our Universe.

- The study of other small celestial bodies, such as **Solar System objects** and **extrasolar planets**, also benefits from high-speed observations, as shall be revealed later.
Our working definition of high time-resolution astrophysics (HTRA) *in the optical* is a technological one.

It is based on the typical CCD frame rates achievable with common-user instrumentation on the world’s largest telescopes:

- **Non-HTRA:** Frame rates of greater than one per minute.
- **HTRA:** Frame rates of less than one per minute.

Hence HTRA nearly always requires specialist instrumentation.
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THE DETECTION OF LIGHT

Nowadays, you won’t find photographic plates, APDs or photomultiplier tubes at the largest telescopes in the world. You won’t even find CMOS detectors, such as used in your mobile phones or most digital cameras.
Strictly speaking, it is not necessary to know the spatial distribution of the photons in order to make a photometric measurement - all that matters is the total number of photons received from the source.

So, it is possible to perform photometry with a single-pixel detector, such as a photomultiplier tube or an avalanche photodiode (APD).
SINGLE PIXEL vs MULTI-PIXEL DETECTORS

SINGLE-PIXEL DETECTORS ARE FAST, BUT:

- The pixel must be larger than the seeing disc and typical guiding errors of the source. So extra sky is collected, degrading the SNR.
- Photometry of extended sources and crowded fields is impossible.
- Only one star at a time can be recorded, so they cannot be used in non-photometric conditions.
- Simultaneous measurement of the sky brightness is difficult.
MULTI-PIXEL DETECTORS ARE PREFERRED BECAUSE:

- The same instrument can provide imaging and photometry.
- Software apertures that are adjustable during data reduction can be used, maximising SNR.
- Photometry of crowded fields and extended sources is possible.
- Simultaneous measurement of comparison stars is possible, allowing transparency variations to be corrected.
- Simultaneous measurement of the nearby sky is straightforward.
THE DETECTION OF LIGHT

• The detector of choice is the **Charge-Coupled Device (CCD)**, for which Willard Boyle and George Smith were awarded a Nobel Prize in 2009.

• The problem is, although almost perfect detectors in almost every other respect, CCDs are slow to read out – up to minutes between frames.
Photons hit the silicon and create electrons (known as *photoelectrons*).

On completion of the exposure, the electrons are “clocked out”, counted, and then digitised.

Only when all of the electrons have been “read out” can the next exposure begin.
FRAME-TRANSFER CCDs

• Speeding up the clocking and readout of CCDs results in unacceptably poor charge transfer and high detector noise.

• So how can we read out CCDs faster? One solution is to use a frame-transfer architecture.

• Frame-transfer CCD demo....
BINNING AND WINDOWING

As well as using a frame-transfer architecture, CCDs can be further speeded up as follows:

• Use of multiple outputs.
• On-chip binning.
• Windowing.
• Use of high-speed data acquisition systems.
• Reducing the clocking time.
• Reducing the time taken to measure the charge in each pixel.
ULTRACAM Demo.
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ULTRACAM is a high-speed (0.05-300 Hz), triple-beam optical CCD camera with a 5’x5’ field of view.

It was built by a consortium from the Universities of Sheffield, Warwick and the UKATC, Edinburgh.

ULTRACAM is a private instrument which mounts on the 4.2m WHT, 8.2m VLT and 3.5m NTT.
4.2m WHT La Palma
8.2m VLT Chile
3.5m NTT Chile
ULTRACAM is a re-imager – the native WHT platescale of 4.51”/mm is demagnified to the CCD platescale of 0.3”/pixel (where 1 pixel = 13µm).

Magnification, \( M = s_{\text{cam}} / s_{\text{coll}} = F_{\text{cam}} \theta_2 / F_{\text{coll}} \theta_2 = F_{\text{cam}} / F_{\text{coll}} \approx 5. \)
DATA ACQUISITION SYSTEM

- Telescope
- TEC control
  - u' CCD
  - g' CCD
  - r'/i'/z' CCD
- SDSU CCD controller
- 0.5 TByte SCSI disk array
- PCI bus instrument control PC (RTAI)
- 2 x 250MHz fibres
- parallel port interrupt line
- GPS
  - lightning protection
  - outside
- Local area network
- 0.5 TByte USB disk
- Data redn PC (Linux)
- Control room
Setting an exposure time with a frame-transfer CCD is more complex than with a normal CCD.

ULTRACAM can shift the image area into the storage area only when there is room in the storage area to do so.

Hence the fastest exposure time is given by the time it takes to empty the storage area, which depends on the number of pixels being read out, their location, and the digitisation speed.

Reading out the whole storage area takes ~5 s (0.2 Hz), so this is the full-frame readout time.

Reading out only 1 pixel takes 25 ms (40 Hz) - the vertical clocking time. This sets the maximum frame rate in this mode, but the exposure time is essentially 0 ms.
To obtain an arbitrarily long exposure time, it is possible to add an **exposure delay**, which allows photons to accumulate for the required amount of time in the image area.

What if you need full frame images but also need a shorter exposure time than 5 s? (e.g. for a flat field or standard star.)

The solution is to use **clear mode** - the data in the image area is dumped prior to exposing for the requested amount of time.

The disadvantage is that clear mode is very inefficient – only a small fraction of the time is spent exposing, just like a normal CCD.
**DRIFT MODE**

- The maximum useful frame rate with two small windows is \(~10\) Hz (0.1 s).
- If you want to go faster than this, you must use drift mode.
- Two small windows are positioned on the border between the image and storage areas.
- Instead of vertically clocking the windows the entire height of the storage area (25 ms), they are only clocked just over the border (~0.5 ms).
- In this case, frame rates of up to 300 Hz can be obtained.
- Disadvantage of drift mode is that pixels accumulate more dark current and sky.
- The latter can be minimized by using the focal-plane mask.
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**SCIENCE WITH ULTRACAM**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>accreting white dwarfs/cataclysmic variables</td>
<td>19%</td>
</tr>
<tr>
<td>black-hole/neutron star X-ray binaries</td>
<td>13%</td>
</tr>
<tr>
<td>extrasolar planet transits and eclipses</td>
<td>11%</td>
</tr>
<tr>
<td>sdB stars/asteroseismology</td>
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</tr>
<tr>
<td>eclipsing, detached white-dwarf/red-dwarf binaries</td>
<td>10%</td>
</tr>
<tr>
<td>isolated/non-accreting white dwarfs</td>
<td>10%</td>
</tr>
<tr>
<td>pulsars</td>
<td>6%</td>
</tr>
<tr>
<td>flare stars</td>
<td>5%</td>
</tr>
<tr>
<td>ultra-compact binaries/double degenerates</td>
<td>5%</td>
</tr>
<tr>
<td>occultations by Titan, Pluto, Uranus, Kuiper Belt Objects</td>
<td>4%</td>
</tr>
<tr>
<td>isolated brown dwarfs</td>
<td>2%</td>
</tr>
<tr>
<td>GRBs</td>
<td>2%</td>
</tr>
<tr>
<td>miscellaneous objects (AGN, contact binaries, etc)</td>
<td>2%</td>
</tr>
</tbody>
</table>

- **443 nights of time**
  - WHT: 283
  - NTT: 120
  - VLT: 40
- **~100 refereed papers**
  - 2 Nature papers
  - 2 Science papers
WHITE DWARFS WITH ULTRACAM

- Cataclysmic Variables (CVs)
  SDSS 1035+0551
  Littlefair et al. 2006, Science, 314, 1578

- Detached white-dwarf/red-dwarf binaries (PCEBs/pre-CVs)
  NN Ser
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- Detached white-dwarf/red-dwarf binaries (PCEBs/pre-CVs)
  NN Ser
1: 7.9 yr, 2.3 M, 3.4 au
2: 15.3 yr, 7.3 M, 5.4 au
NEUTRON STARS WITH ULTRACAM

- **Anomalous X-ray pulsars (AXPs)**
  - AXP 4U0142+61
  - Soft Gamma Repeaters (SGRs)
    - SGR 0501+4516
  - Binary Millisecond Pulsars (MSPs)
    - PSR J2215+5135
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BLACK HOLES WITH ULTRACAM

• GX339-4: X-Ray Binary (XRB)

OCCULTATIONS WITH ULTRACAM

Zalucha et al, 2007, Icarus, 192, 503
OCCULTATIONS WITH ULTRACAM

Makemake (TNO @ 52 AU, 1500 km diameter, no atmosphere)
Ortiz et al. 2012, Nature, 491, 566
EXOPLANETS WITH ULTRACAM

WASP-12b: TRANSIT
WASP-12b: SECONDARY ECLIPSE
EXOPLANETS WITH ULTRACAM

KIC1255754b: VARIABLE TRANSITS
Bochinski et al. 2015, ApJL, 800, L21
KPD 2109+4401

ASTEROSEISMOLOGY WITH ULTRACAM
UNIQUE FEATURES OF ULTRACAM

• High-speed **imaging**
• Three optical bands simultaneously
• Mounted on large telescopes
• Open access policy
**ULTRACAM+NTT 2016-2020+**

- Top-ranked proposal in recent ESO call for instrumentation for the NTT.
- **Permanently** mount ULTRACAM on the NTT in 2016-2020+.
- Open time available through ESO OPC.
- GTO provided to instrument team in return for providing cube and support.
FURTHER INFORMATION ON ULTRACAM

ULTRACAM WEB PAGE:
http://www.vikdhillon.staff.shef.ac.uk/ultracam

ULTRACAM JOURNAL PAPER:
The End.