The Extraordinary Impact of Astronomy on Imaging Technologies

Craig Mackay

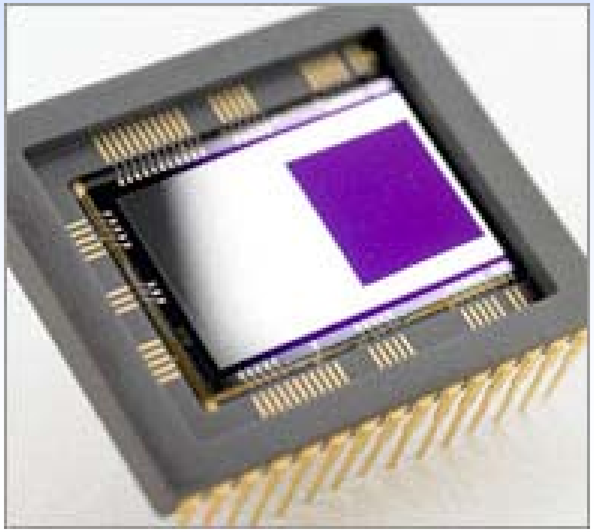
Institute of Astronomy, Cambridge UK

e-mail: cdm@ast.cam.ac.uk; phone +44-(0)1223 337543

UNIVERSITY OF CAMBRIDGE

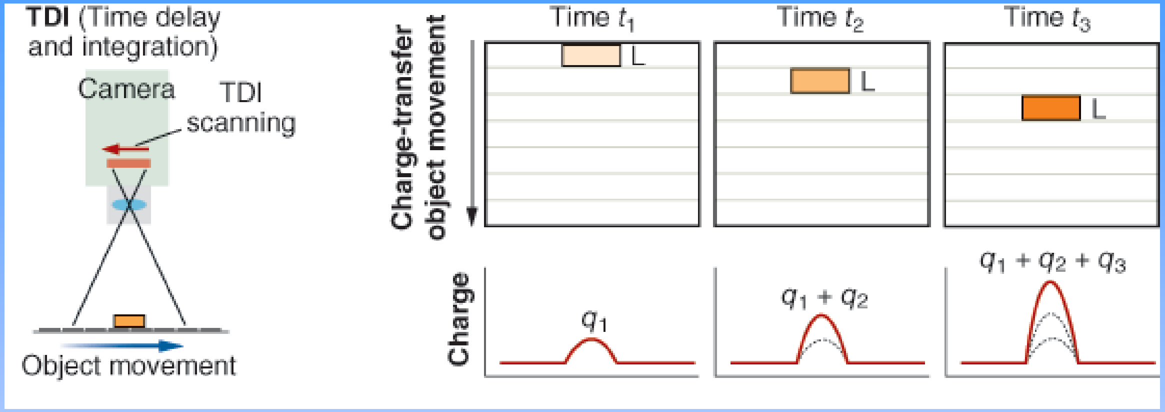
CCD development: background

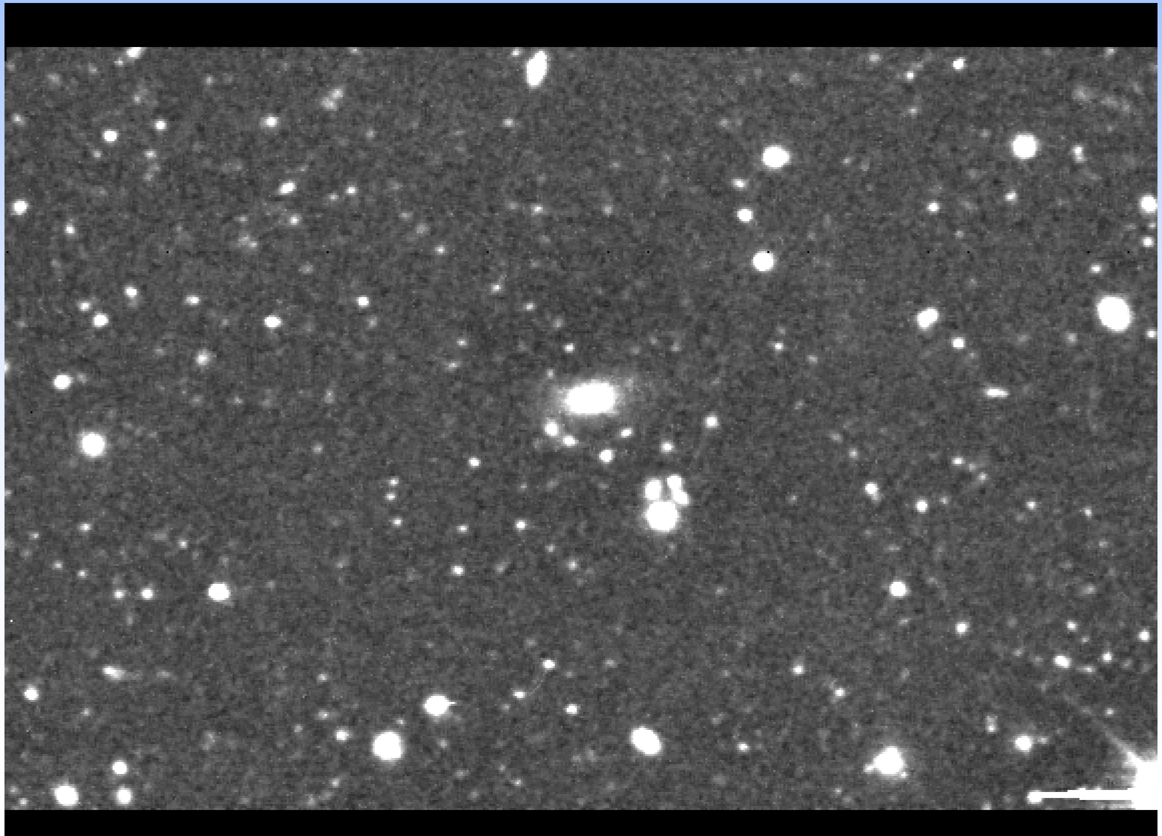
- The first CCDs were developed for use as memory devices.
- Their potential as imagers was recognised very early.
- The first devices were of very poor quality with many dead pixels, generally poor uniformity (often 50% peak to peak sensitivity variations) and mediocre read noise. Bad columns were ubiquitous.
- However they were high detective quantum efficiency and very rugged being solid-state silicon devices.
- The first imagers were really quite small, ~200 x 200 pixels.
- Astronomers worked with CCD manufacturers to improve overall quality. There is no doubt that these interactions were critical in enabling E2V Technologies to dominate the scientific CCD market.



CCD development: background

- Astronomers developed techniques for coping with the poor cosmetic quality such as drift scanning: allowed very low contrast imaging to ~0.1% of sky background.
- Now known as TDI (time delay and integration), widely used for satellite and aircraft surveillance and many other applications.
- Allowed extremely sensitive images to be taken in astronomy reaching levels only recently exceeded by the Hubble Deep Field pictures.
- Also used by Sloan Digital Sky Survey CCD camera.

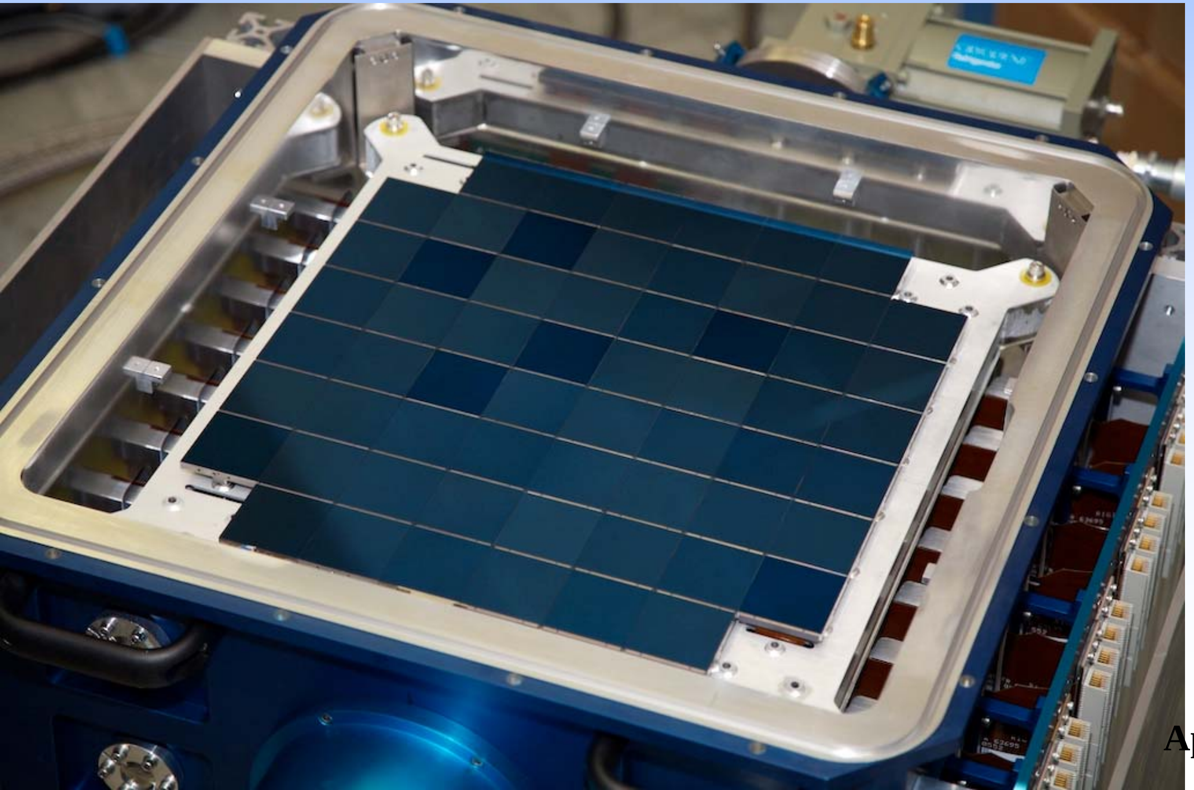




UNIVERSITY OF CAMBRIDGE

CCD development: Modern Applications

- Now individual CCDs with over 111 million pixels are being manufactured and arrays now measured in billions of pixels.
- The image quality is superb with defect free devices common.
- Quantum efficiency is nearly 100% and readout noise as low as 1-3 electrons RMS. In many ways they are virtually perfect detectors.



One of four 1.4 GigaPixel camera for the Pan-Starrs projectusing a new CCD design.

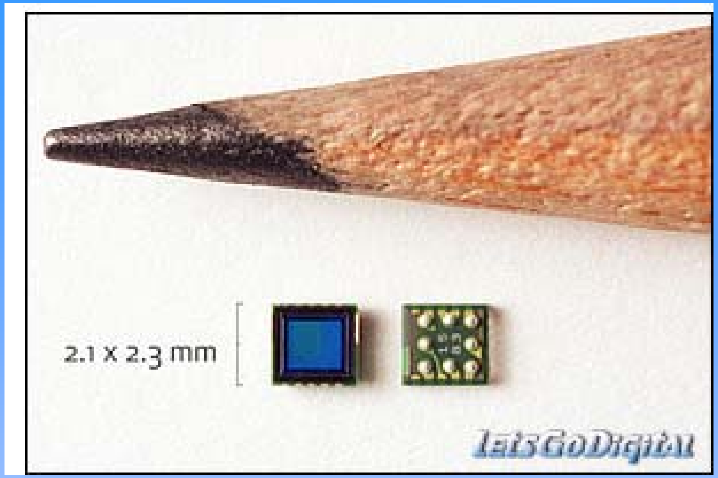
CCD/CMOS: Applications

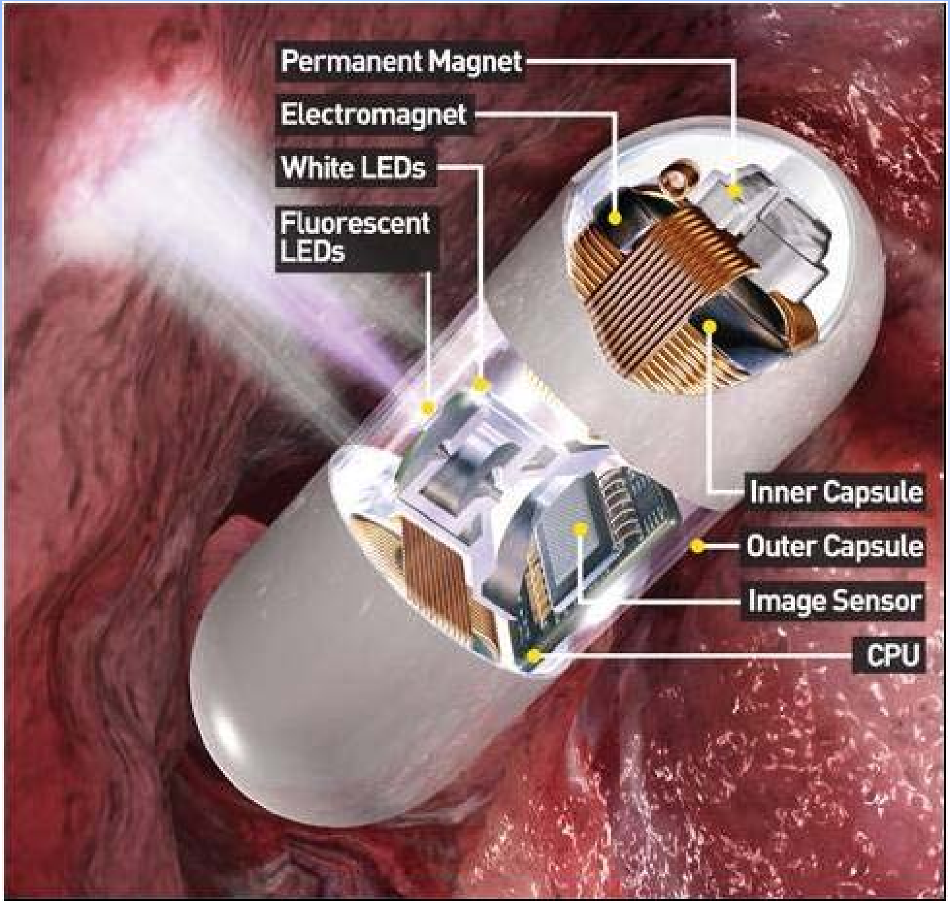
- CCDs are now made in vast numbers. The mobile phone market accounts for approximately 3,000,000 devices per day (approximately 1,000,000 per day for smartphones alone).   This includes the related CMOS imaging detectors.

- It is very difficult to avoid being imaged by CCD/CMOS cameras many times per day.

- These devices are now made in extremely compact forms as well.

- This device is a 5 mm diameter pill that is swallowed. It continually scans the intestines on its way down and relays the images by wireless to the physician.





UNIVERSITY OF CAMBRIDGE

Solid-State Detectors: What Have They Ever Done for Us?

- CCD detectors have been widely used throughout the physical and life sciences and has led to an explosion in our ability to image so much better than had been possible before.
- In particular, the ability to work at very low signal levels when combined with cooling and the ability to work with very wide contrast images made them critical in a number of key areas in research, development and manufacturing.
- Now we also have CCDs that can be read out at high frame rates yet are able to count photons and very low signal levels indeed (< one photon per pixel per 1000 frames).
- Astronomers have been and still are the gatekeepers on high quality imaging technology with solid-state detectors.
- By working with manufacturers as well as researchers in many other areas it has been possible to have an impressive influence on the development of many disparate research fields.
- This symbiotic relationship has led to a number of important patents and technological developments.

Solid-State Detectors: Applications

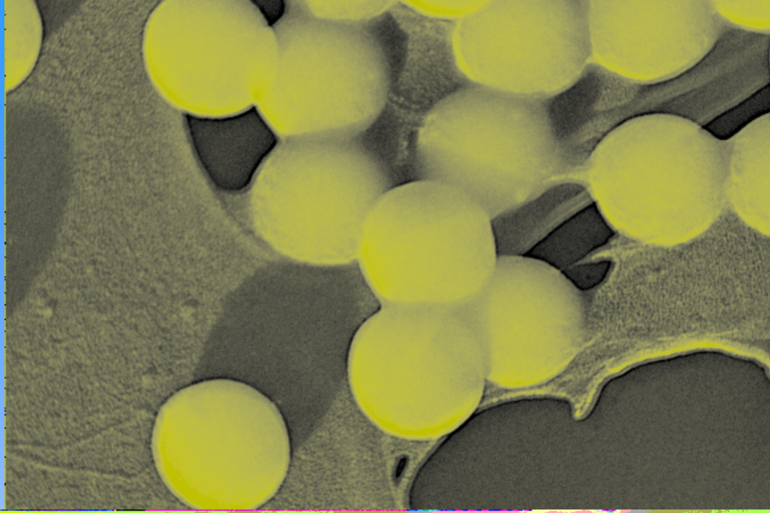
- Application areas include

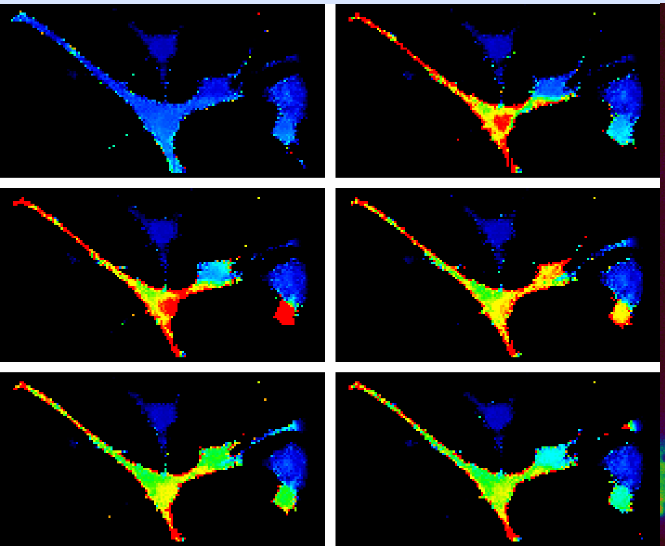
✓ life sciences (automated DNA sequencing, protein electrophoresis, gene probe work, monoclonal antibody searches).

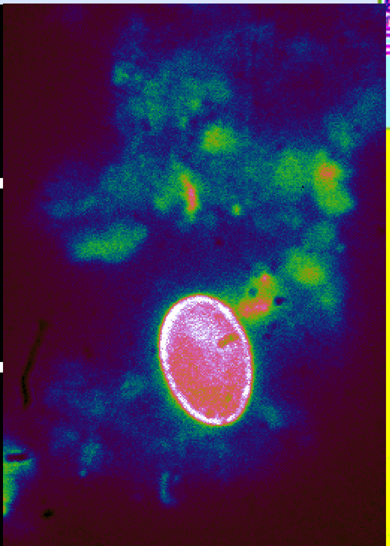
✓ physical sciences (x-ray imaging for materials inspection, electron beam imaging).

✓ medical sciences (dental, internal examinations, x-ray fluoroscopy).

✓ surveillance (security, battlefield, crime prevention and detection).







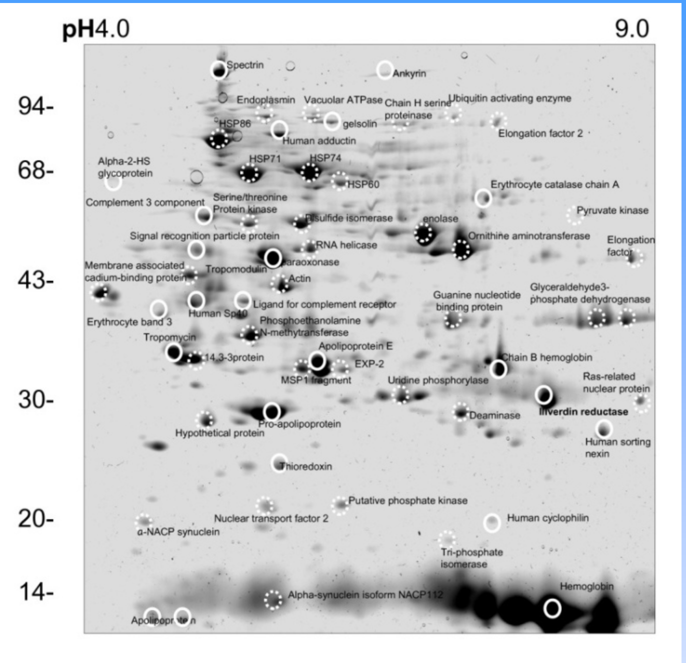
Automated DNA Sequencing

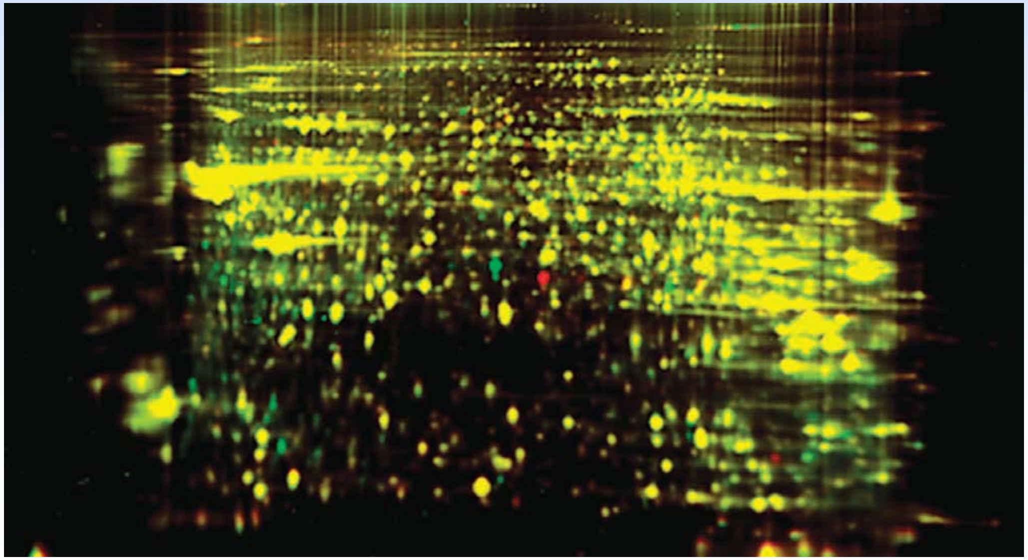
- The use of cooled, slowscan CCD cameras as developed for astronomy for DNA sequencing work was patented in Cambridge.
- They use a variant on drifts scan/TDI technology.
- Key technology needed to make The Human Genome Project successful by increasing the length of the DNA strand that could be sequenced in one procedure.
- Every machine used for the Human Genome Project used one of these patented cameras.
- Many thousands of these machines have been manufactured, each costing between £250K and £800K.

UNIVERSITY OF CAMBRIDGE

Two-Dimensional Gel Electrophoresis

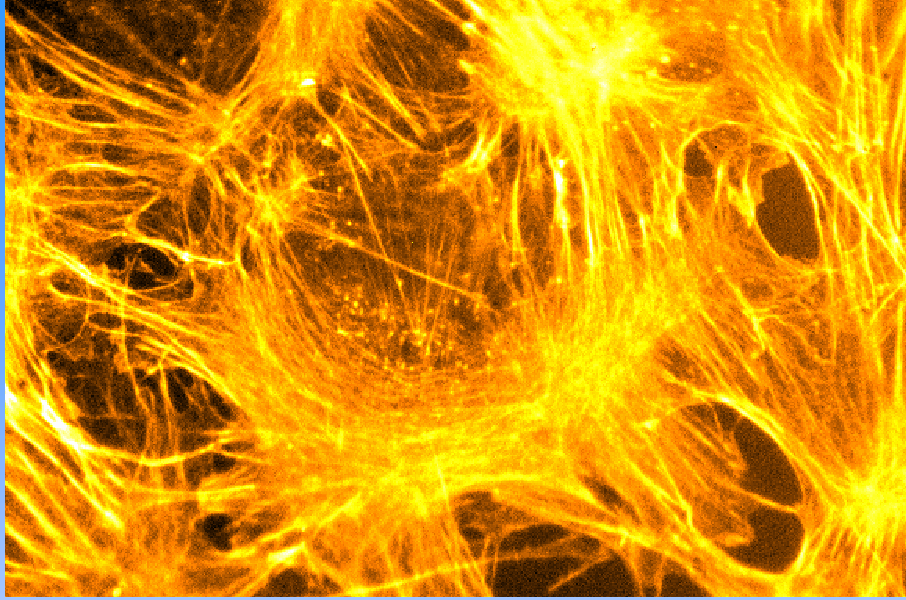
- The same patent was relevant to protein electrophoresis on two-dimensional gels.
- Proteins are uniquely defined by their mass and electric charge.
- They may be separated into dimensions in this way allowing detailed and complex analysis of protein samples.
- Proteins fluorescently labelled are imaged with dramatically greater sensitivity than previously possible.
- In many cases it is possible to identify proteins associated with disease without prior knowledge of what the protein might be.
- A key approach in the development of pharmaceuticals.



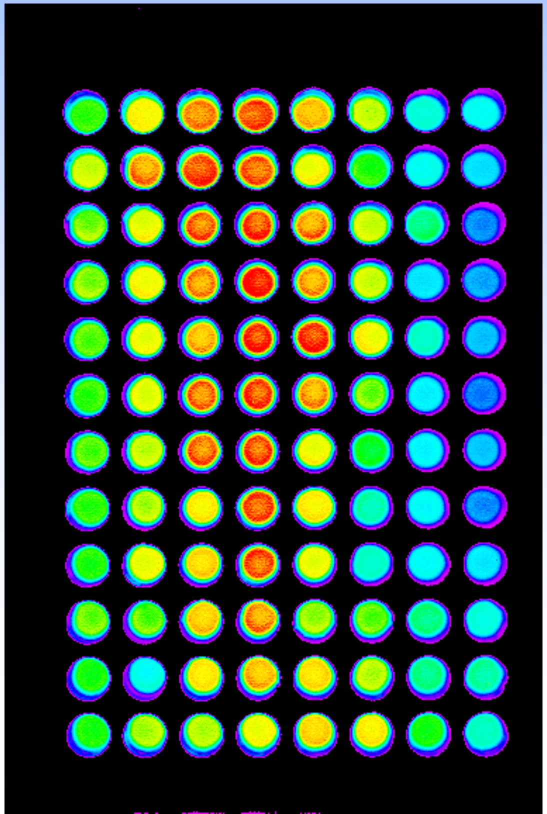


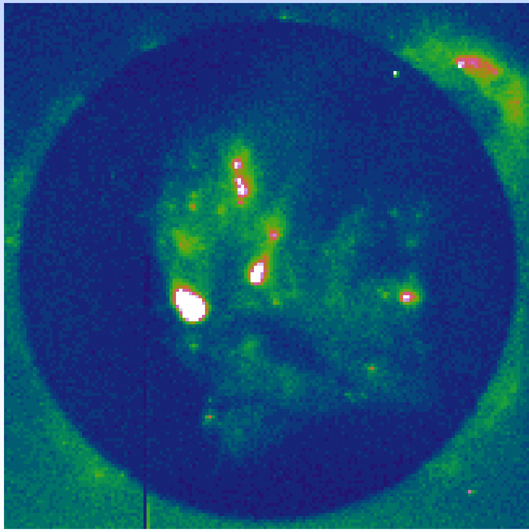
UNIVERSITY OF CAMBRIDGE

Other Life Science Applications



- Scientific CCDs are widely used in optical microscopy (top right).
- By reducing greatly the amount of fluorescent dye needed to be added to cells, and reducing greatly the ultraviolet illumination needed the metabolism in cells is much more normal.
- Bioluminescence allows diseased parts of crop leaves to be identified long before they are visible to the eye (far right).
- Gene probe technologies allow samples to be screened in high-volume for next-generation sequencing related research.

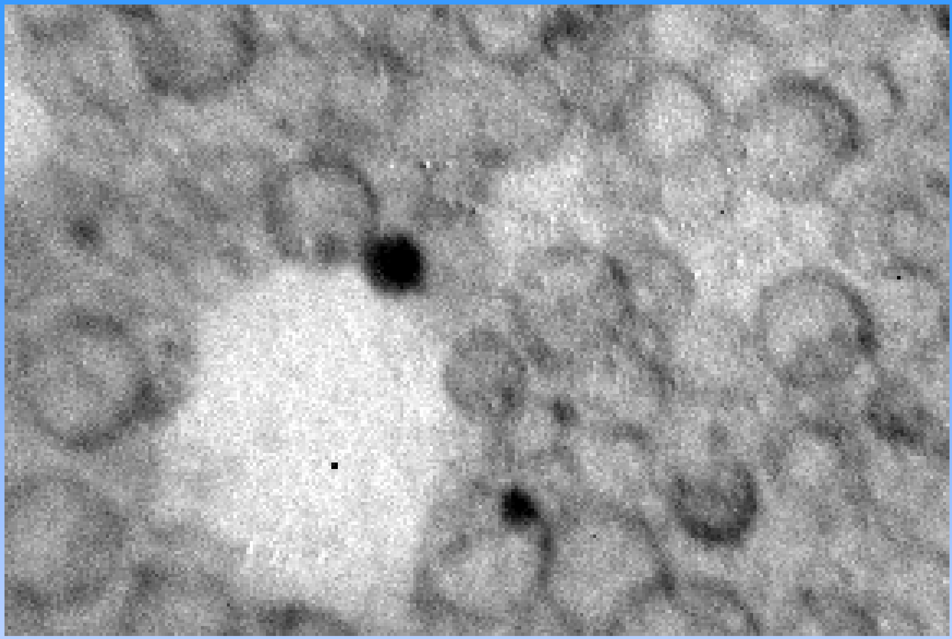


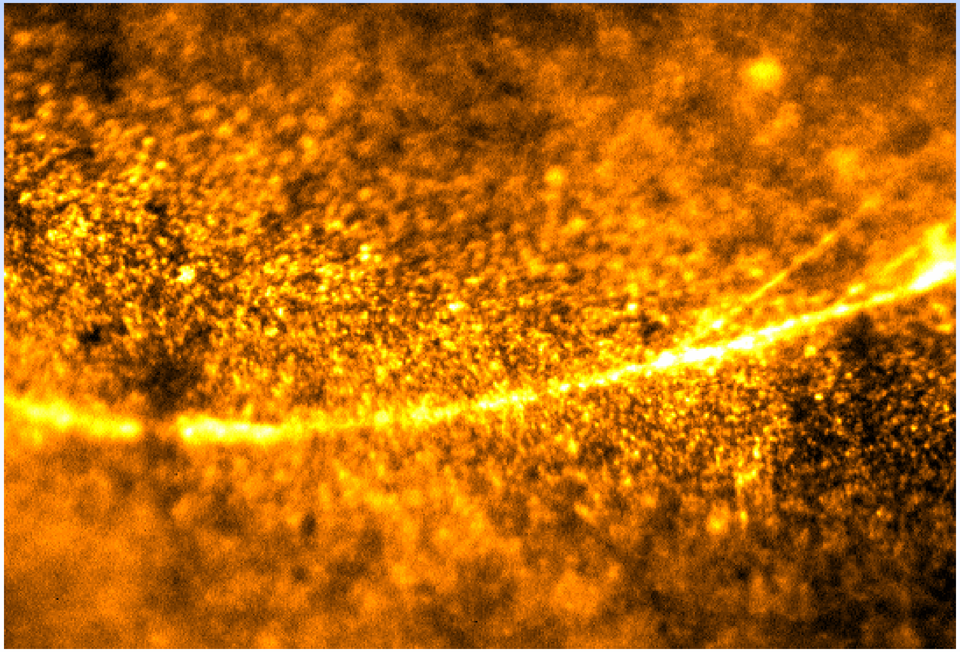


UNIVERSITY OF CAMBRIDGE

Material Science Applications

- Use of cooled scientific CCDs virtually identical to those used by astronomers has greatly improved the quality of x-ray imaging systems because of their ability to provide very low contrast images.
- Composite plastics with hollow glass microspheres are used in stealth aircraft. The voids in the material compromise performance greatly (top right).
- Ceramic ball bearings are key to the performance of the next-generation jet engines because of their extraordinary heat tolerance.
- Micro cracks (bottom right) can cause damaging disintegration. Many are almost impossible to detect without CCD-based x-ray and optical systems.





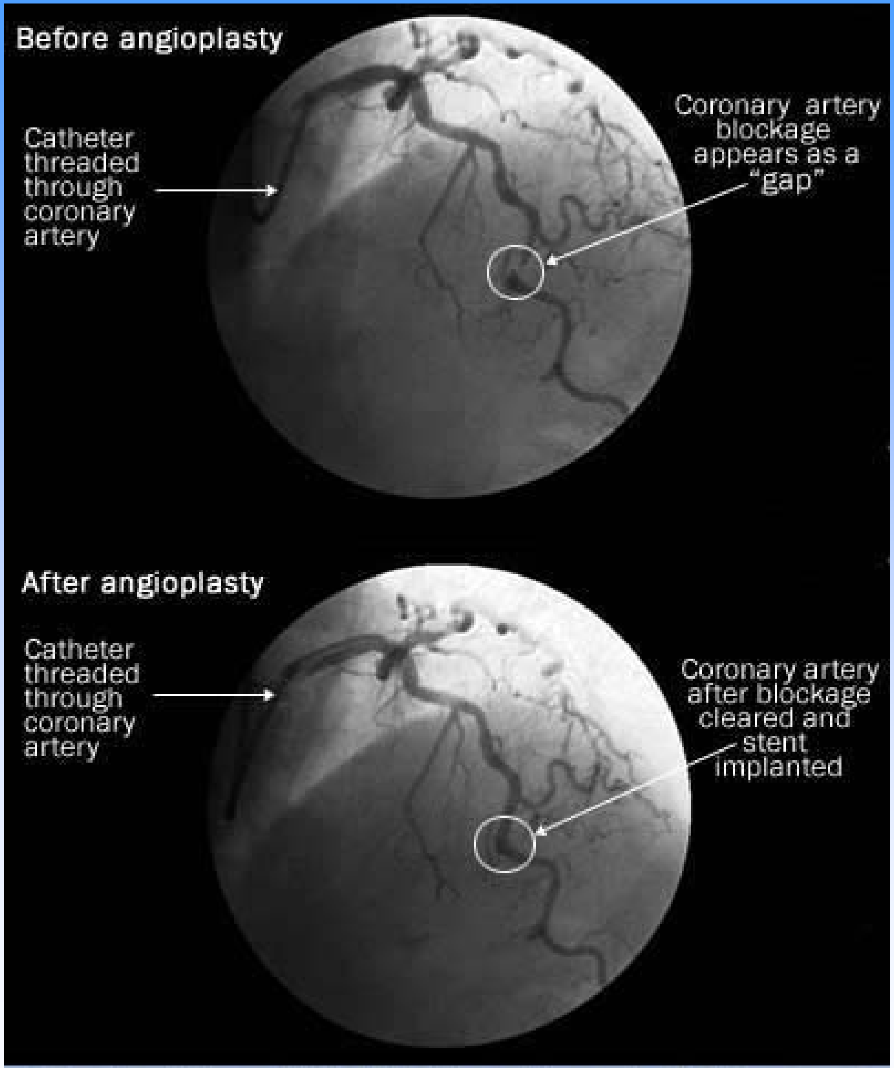
UNIVERSITY OF CAMBRIDGE

Medical Science Applications

- Solid-state detectors are key for many medical cardiology procedures. Fluorescein angiography has revolutionised treatment for atherosclerosis.

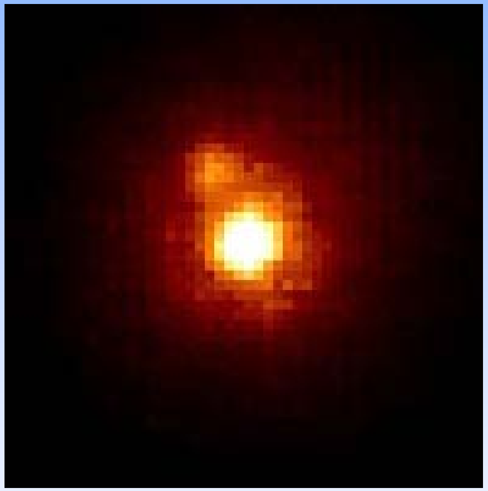
- Many systems use cooled CCD cameras along the lines patented, also in Cambridge, over 20 years ago.

- Systems are increasingly wide field and are beginning to use amorphous silicon technology which is a direct spin out from the CCD/CMOS world.



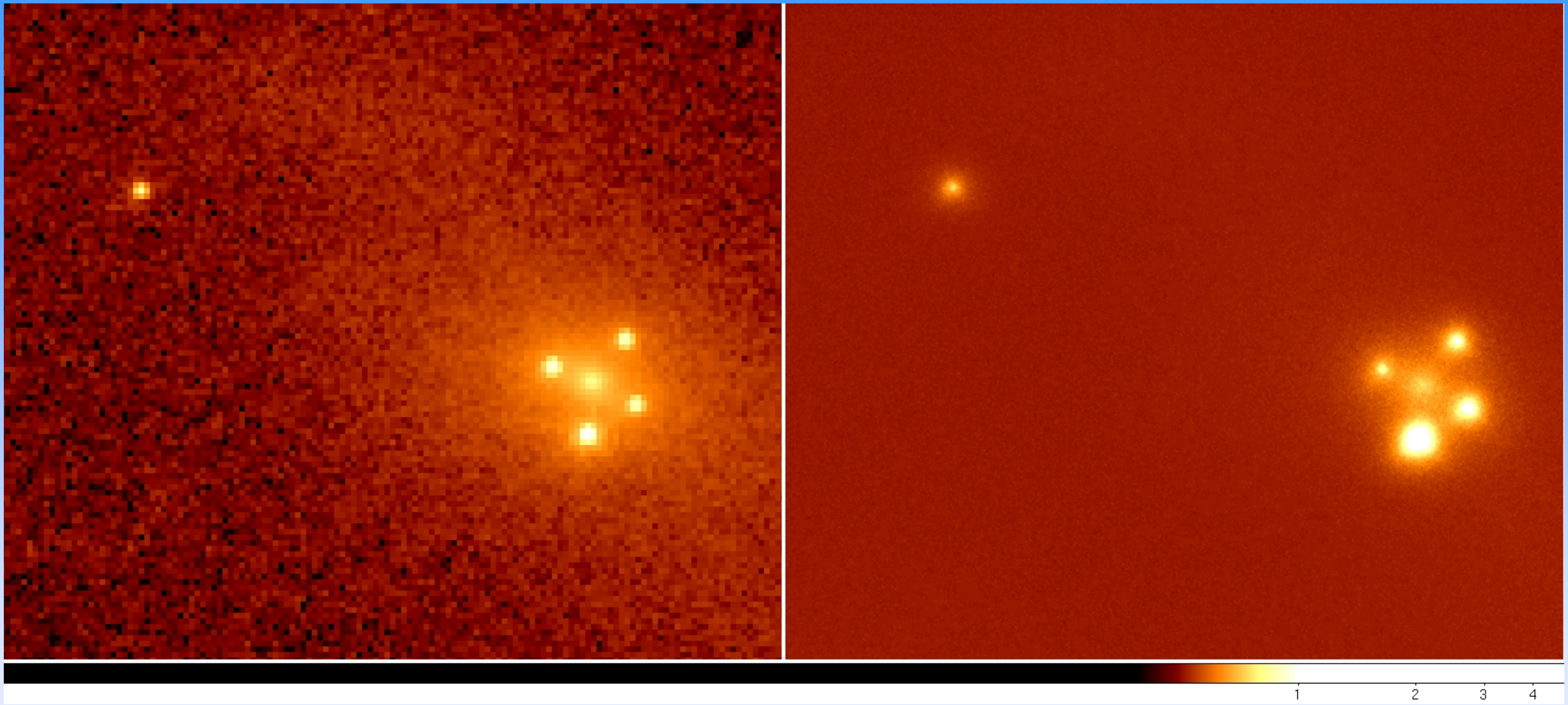
Photon counting CCDs: applications

- Lucky imaging is currently the only method that allows diffraction limited imaging in the visible on ground-based telescopes.
- The key technology is the high-speed photon counting EMCCD cameras to freeze image motion due to atmospheric turbulence.
- The sharpest images are selected, then shifted and added to give an output image.
- This gives near Hubble resolution routinely in the visible. Science targets can be much fainter (I > 25 mag).



0.12 arcsec binary, $\Delta_{mag} \sim 2.5$ imaged with LuckyCam on the NOT 2.5m telescope, La Palma

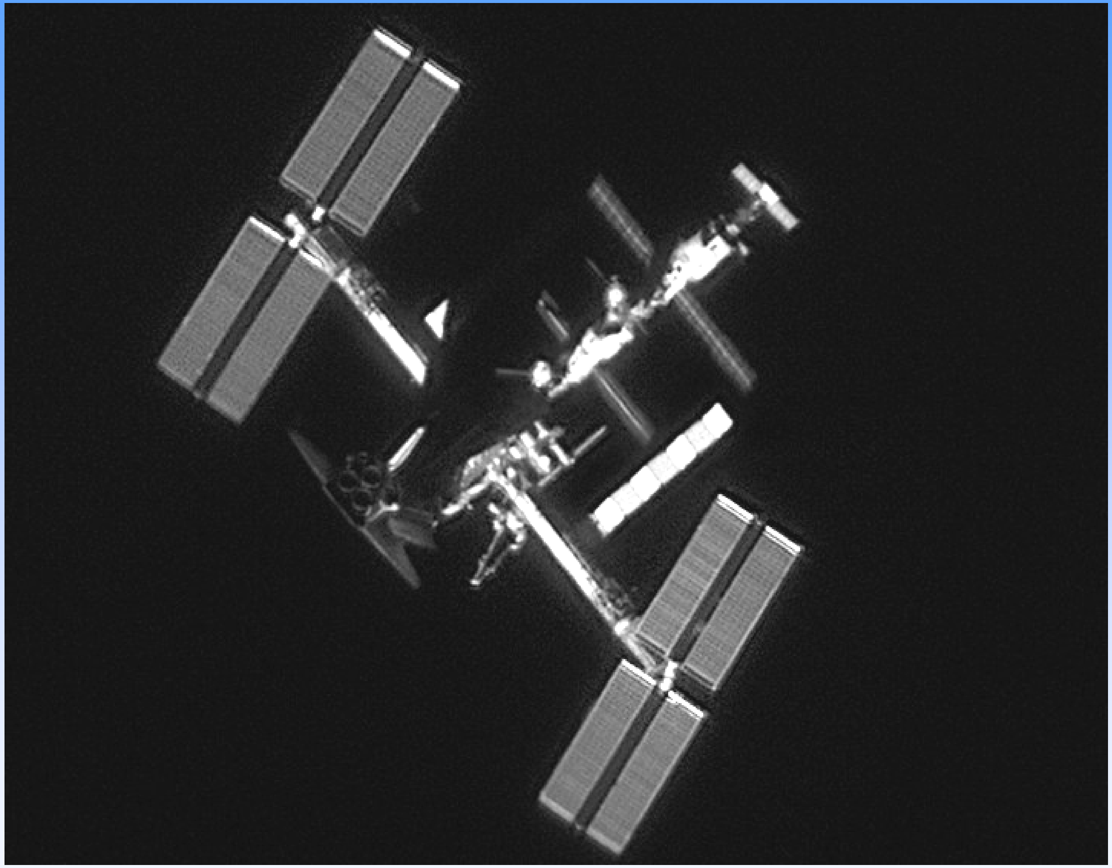
The Einstein Cross



- (left): HST Advanced Camera for Surveys (ACS). (right): Lucky Image from the NOT (2.5m, La Palma).
- The central slightly fuzzy object is the core of the nearby Zwicky galaxy, ZW 2237+030 that gives four gravitationally lensed images of a distant quasar at redshift of 1.7

UNIVERSITY OF CAMBRIDGE

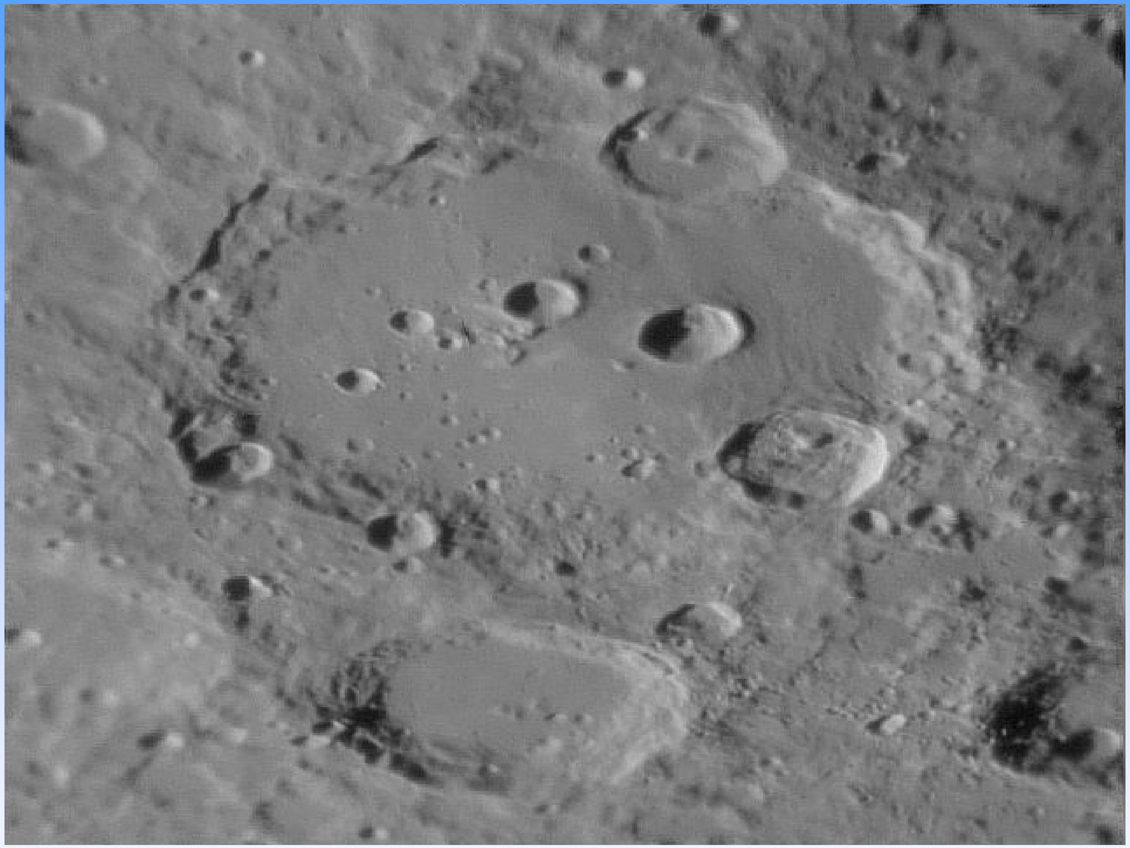
New Results with Lucky Imaging



- This image of the International Space Station, with Space Shuttle Atlantis and a Soyuz Spacecraft in attendance was taken with a ground-based telescope using Lucky Imaging in June 2007.
- Resolution was about 20 cm at an altitude of 330 km altitude, or ~ 0.12 arcsec.
- Downward looking resolution is much better, 20 marcsecs or ~ 2 cm.

UNIVERSITY OF CAMBRIDGE

New Results with Lucky Astronomy

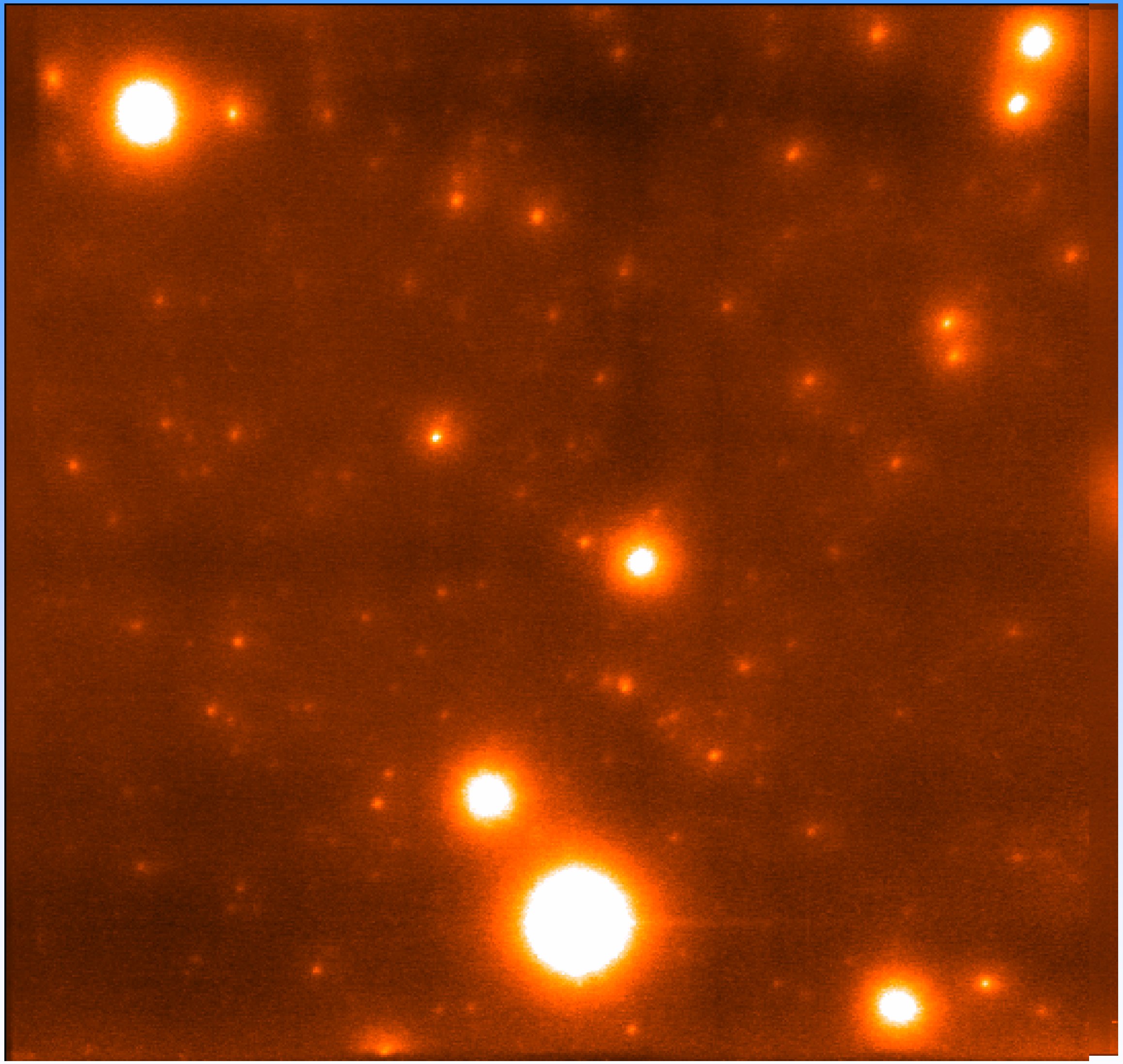


(Images courtesy Wah!, Hong-Kong)

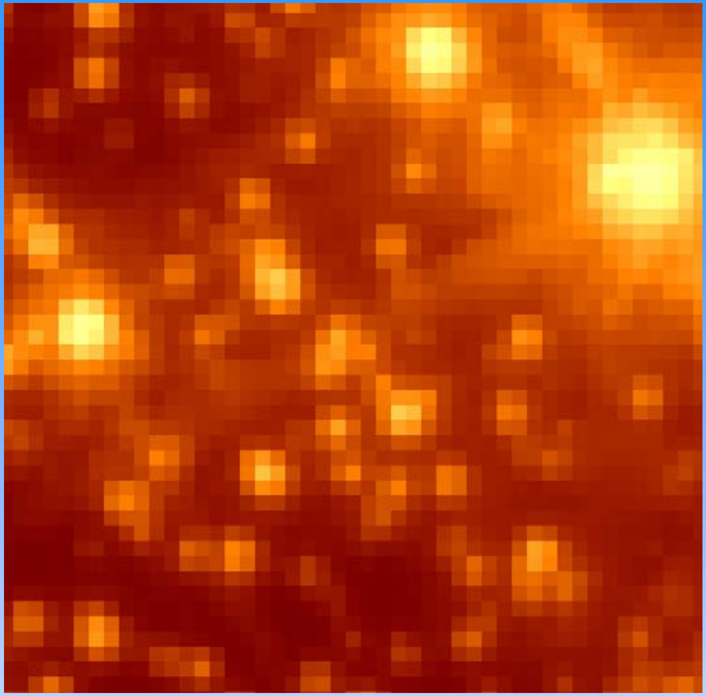
- Techniques are also very popular with amateur astronomers.
- This shows a short movie of the moon taken under poor conditions (roof of skyscraper in Hong Kong!).
- Wah! used Registax Lucky software.

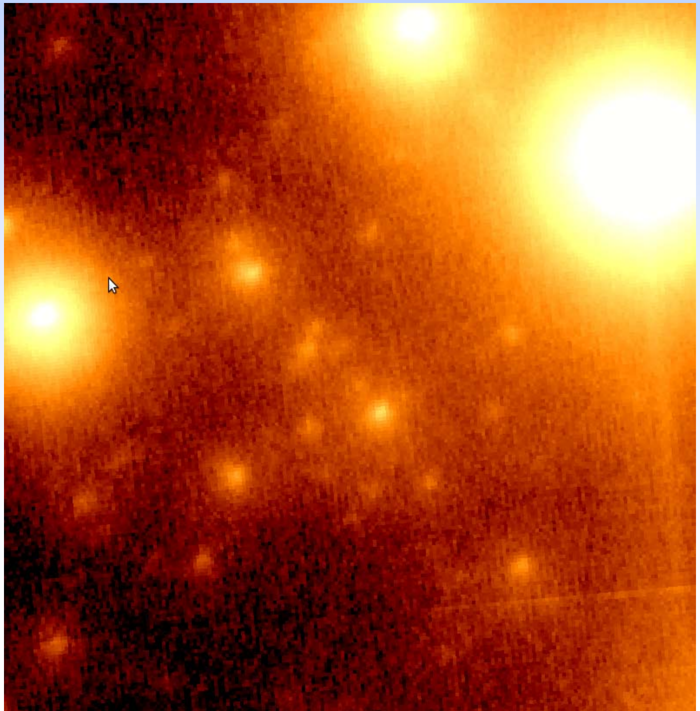
Large Telescope Lucky Imaging.

- Globular cluster M13 on the Palomar 5m.
- Natural seeing ~ 650 mas.
- Imaged via the PALMAO system and our EMCCD Lucky Camera.
- Achieved 17% Strehl ratio in I-band, giving ~35 mas resolution.
- This is the highest resolution wide-field image ever taken in the visible/I-R from space or from the ground.



Large Telescope Lucky Imaging.





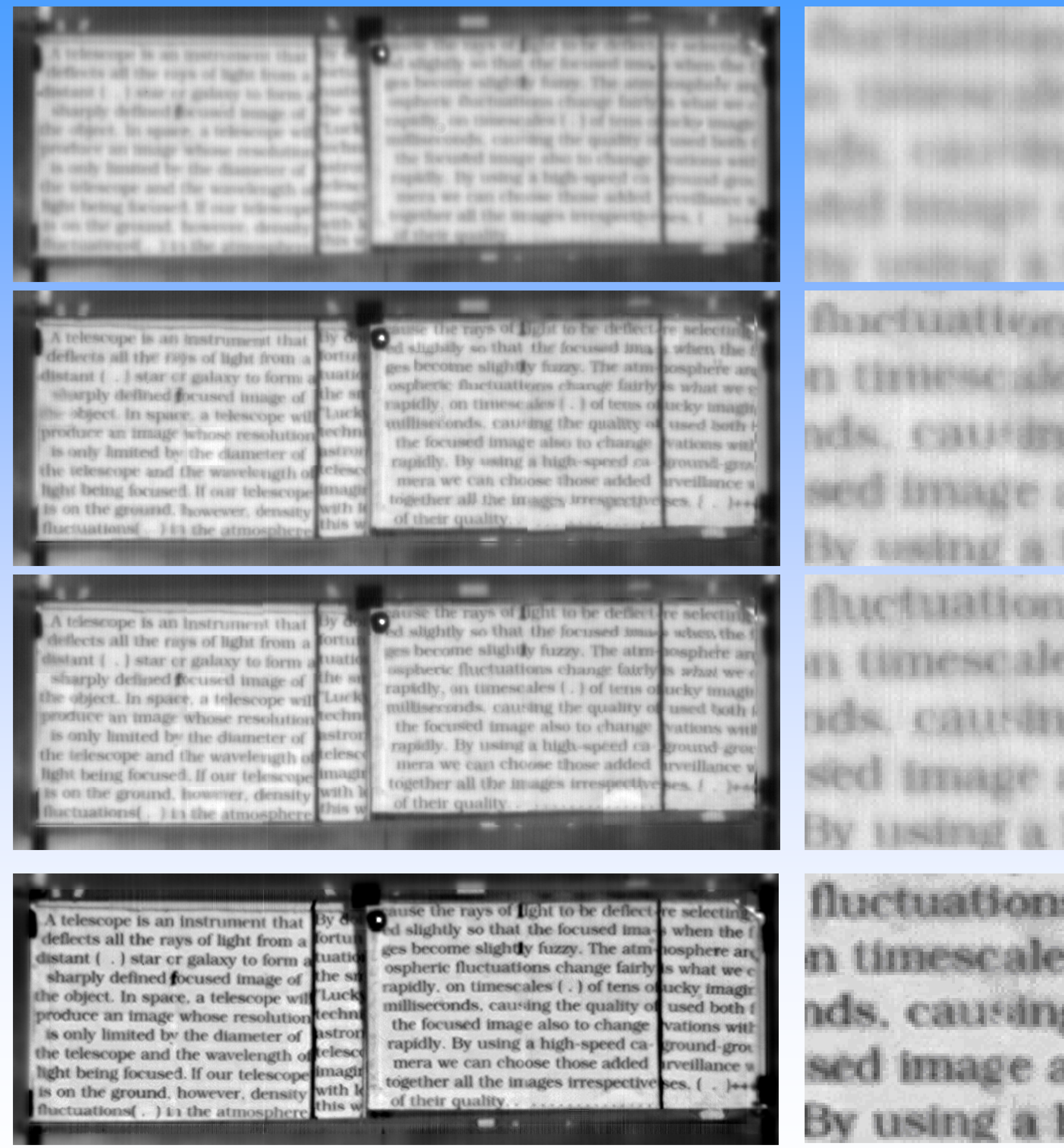
- The comparison of our system, both without Lucky/AO and with Hubble Advanced Camera (ACS) is quite dramatic.

- The Lucky/AO images have a resolution ~35 milliarcseconds or nearly 3 times that of Hubble.

UNIVERSITY OF CAMBRIDGE

Surveillance with Ground-Based Lucky Imaging

- We see here selected images using different selection rates.
- The top image is the sequence average (what you would get with a long exposure image).
- Others show selections of 100%, 10%, 1% and 1% post-processing.
- The resolution improvement is dramatic.
- We typically are able to reduce the effective distance of a target by a factor of 8-12.



UNIVERSITY OF CAMBRIDGE

Conclusions.

- Astronomers were and still are centrally involved in the development of high-performance solid-state imaging systems.
- This symbiotic relationship between them and the manufacturers has been extraordinarily productive.
- Astronomers were able to patent key technologies that enabled substantial improvements instrument performance in a wide range of fields.
- In this way astronomers have contributed very greatly to industries with turnovers of many billions of dollars per year.

- Instrumental research in university departments in astronomy has been extremely productive.
- It is very important that instrumental development work should not be concentrated in the major observatories that are solely dedicated to building common user instruments.
- It is innovation and invention that are key to the future.