Introduction to Astrophysics

Michaelmas Term, 2020: Prof Craig Mackay

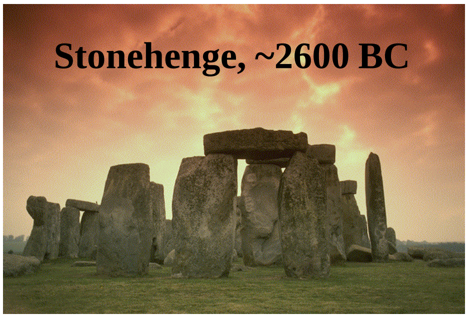
Module 3:
- Telescope and techniques: the importance of technology.
- The transparency of the atmosphere. The best existing telescopes.
- Telescope and techniques: Planned future Extremely Large Telescopes (ELTs)
- Imagers, spectrographs, diffraction limit.
- Atmospheric seeing, adaptive optics.
- Spatial resolution of interferometers, signal-to-noise calculations.

How do we learn about the Universe?

- Astronomy is almost entirely the measurement and interpretation of the electromagnetic radiation that arrives at the Earth.
- Discovery and understanding are driven by technology.

- Neutrinos
- Cosmic rays
- Meteorites
- Moon rocks
- Solar wind
- Space probes

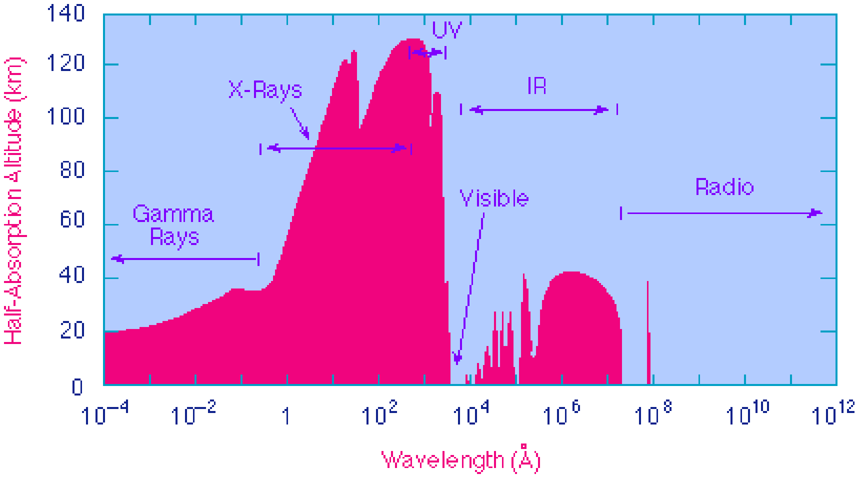
These are the only sources of extra-terrestrial information other than electromagnetic radiation.



Stonehenge, ~2600 BC

Galileo 1609

New wavelength regimes, e.g. radio astronomy.



The transparency of our atmosphere

The biggest and best telescopes

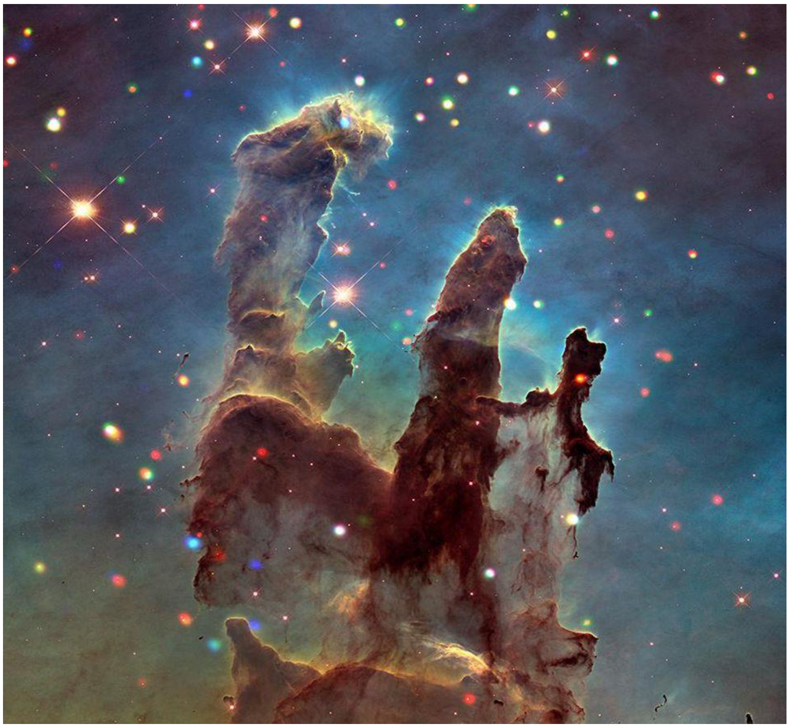
- Hubble Space Telescope (HST), UV, optical, IR
- Chandra, X-ray space telescope
- Compton, Gamma-ray space telescope
- Spitzer infra-red space telescope
- James Webb Space Telescope (JWST), optical, IR-optimised (2021??)
- Herschel (far IR)
- Planck (Cosmic Microwave Background survey)
- The Keck Telescopes, 2x10m, Hawaii
- The Very Large Telescope (VLT), 4x8.2m, Chile
- Gemini, 2x8m, Hawaii and Chile, Subaru, 8.2m, Hawaii
- Large Binocular Telescope (LBT), 2x8.4m, Arizona (2007)
- GranTeCan, (GTC) 10.4m, Canary Islands (2007)
- Very Large Array (VLA), radio telescope, New Mexico
- James Clerk Maxwell Telescope (JCMT), 15m sub-mm, Hawaii
- Atacama Large Millimetre Array, (ALMA), Chile (2010)

+ HET
&
SALT

The Hubble Space Telescope

- 2.5m. 1990 to at least 2025.
- Recently refurbished with new and repaired instruments.
- Optical (121nm) to near IR (2.2 microns)

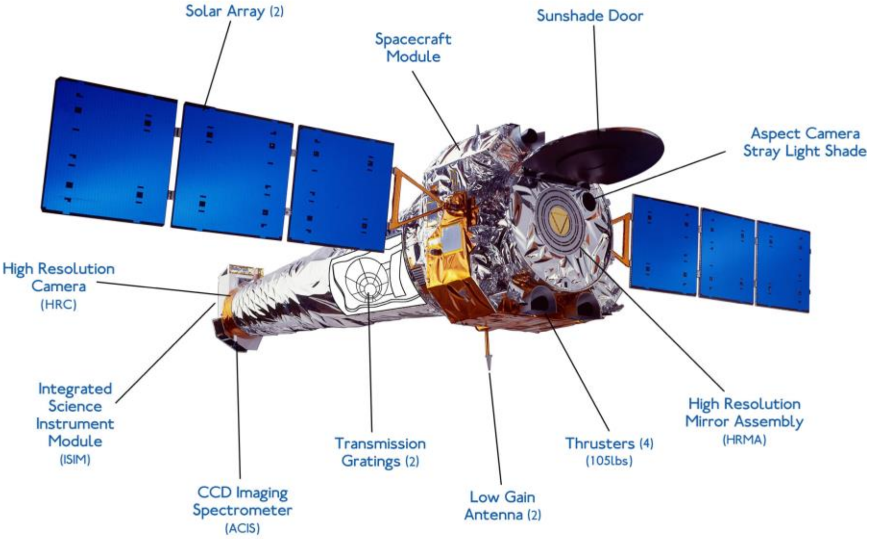
- Extraordinarily successful and productive telescope at least in part because it was repairable so instruments were improved and replaced regularly.



The Eagle Nebula, M16.

- Dusty cocoons containing newly formed stars are being evaporated by bright young stars, exposing the regions where new stars are being created.
- HST Image.

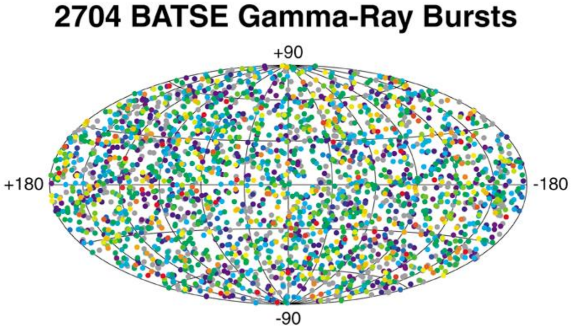
Chandra, X-ray telescope, launched July 1999



Cen A, X-ray image, Chandra

Compton Gamma Ray Observatory (CGRO)

Launched Apr 1991
brought back Jun 2000



Discovered many gamma-ray bursts (GRBs)

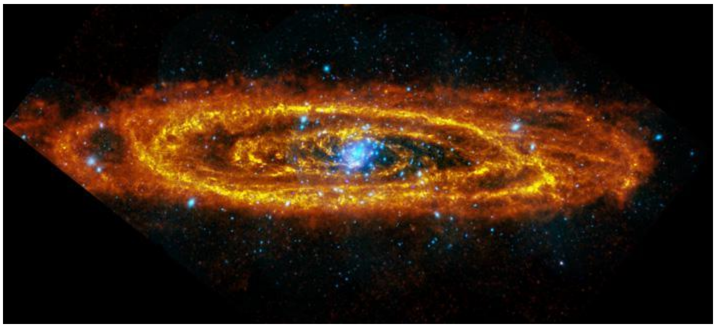
The Spitzer Space Telescope

Decommissioned in 2020 after 17 years in operation.

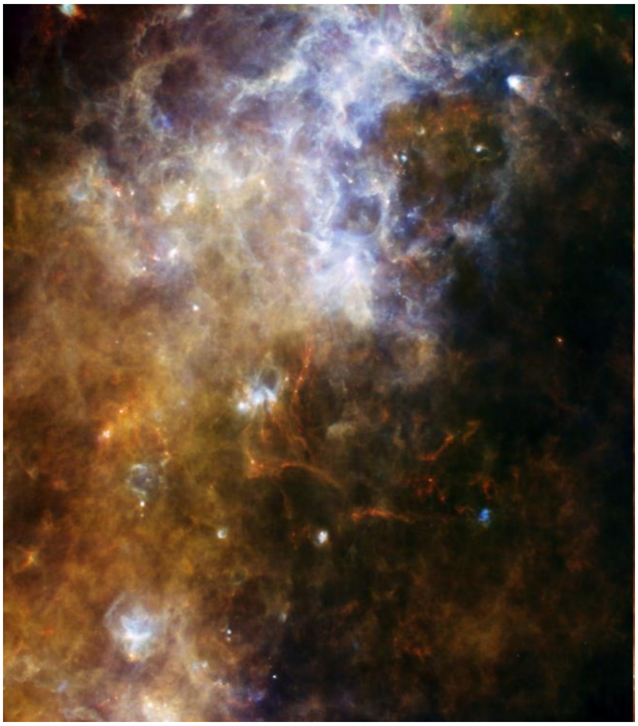
- Earth-trailing orbit
- Observes wavelengths 3-180 microns, very far infra-red.
- 0.85m telescope
- Imaging and spectroscopy
- Study cool or obscured objects

ESA's Herschel Space Telescope

- Largest single mirror ever built for a space telescope, 3.5-metres in diameter.
- Will collect long-wavelength radiation from some of the coldest and most distant objects in the Universe.
- The only space observatory to cover a spectral range from the far infrared to sub-millimetre. Cryogen lifetime was roughly as expected ~ 4 years.



Orange represents infrared light from Herschel, while Blue shows the x-rays from XMM-Newton.

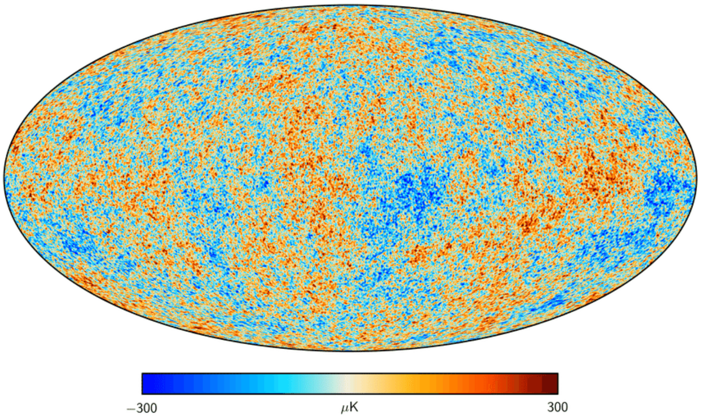


ESA’s Herschel Space Telescope

- The images show intricate filamentary structures made from cold interstellar material. This matter feeds galactic star formation, and this image provides new insights into these highly turbulent processes.
- This is a 2 degree square image of the Milky Way from 5 colour bands (blue denotes 70 µm and green 160 µm emission, while red is the combination of the emission from all three SPIRE bands at 250/350/500 µm.)
- Some material here is at 10K only.

ESA’s Planck Space Telescope

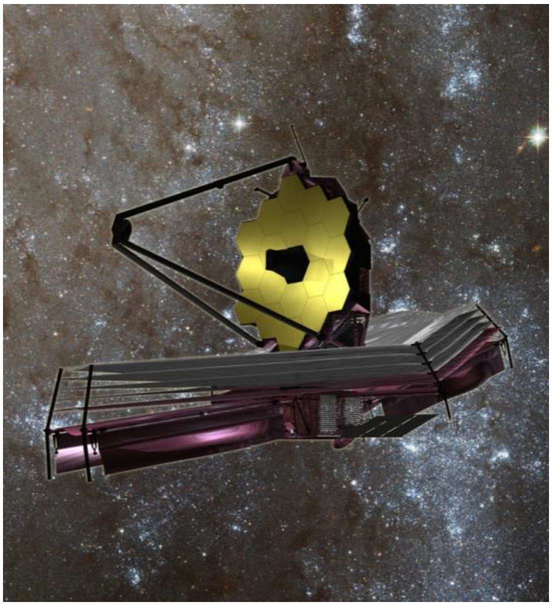
- Planck's objective is to analyse, with the highest accuracy ever achieved, the remnants of the radiation that filled the Universe immediately after the Big Bang - this we observe today as the Cosmic Microwave Background.
- Launched 2009 (with Herschel) on an Ariane rocket. Now ended.



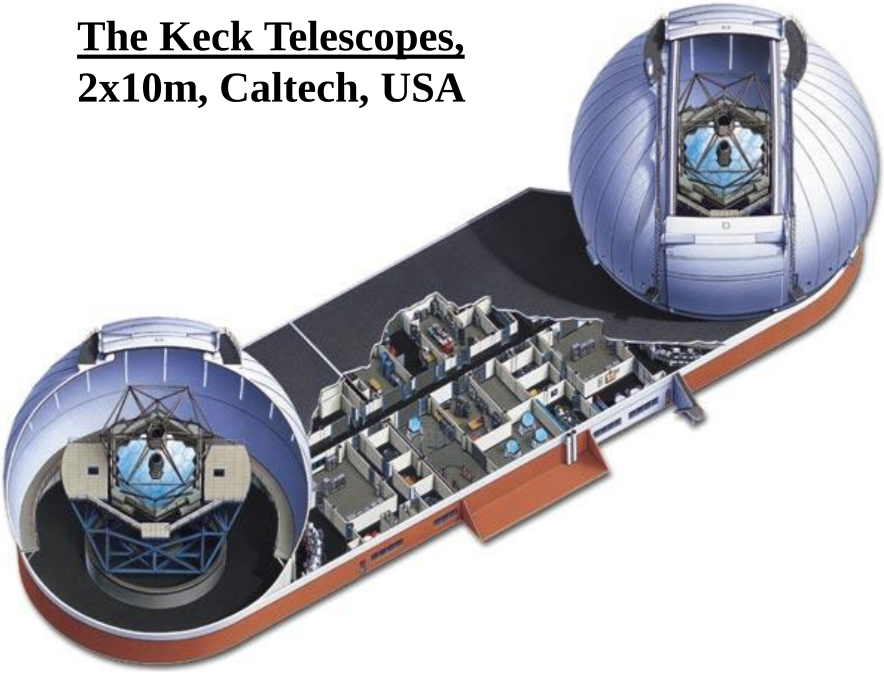
- Showed the background radiation in the universe is remarkably uniform wherever you look.
- Map scaled for peak-to-peak range of 600 µK.

James Webb Space Telescope

- Initial contract awarded for $825M!
- Current cost $13B
- Launch date 2021(???), on Ariane 5
- 0.6-28um
- 6.5m telescope
- Optimised for IR so angular resolution actually poorer than HST
- Not repairable! (at L2).



The Keck Telescopes, 2x10m, Caltech, USA



The VLT (Very Large Telescope)

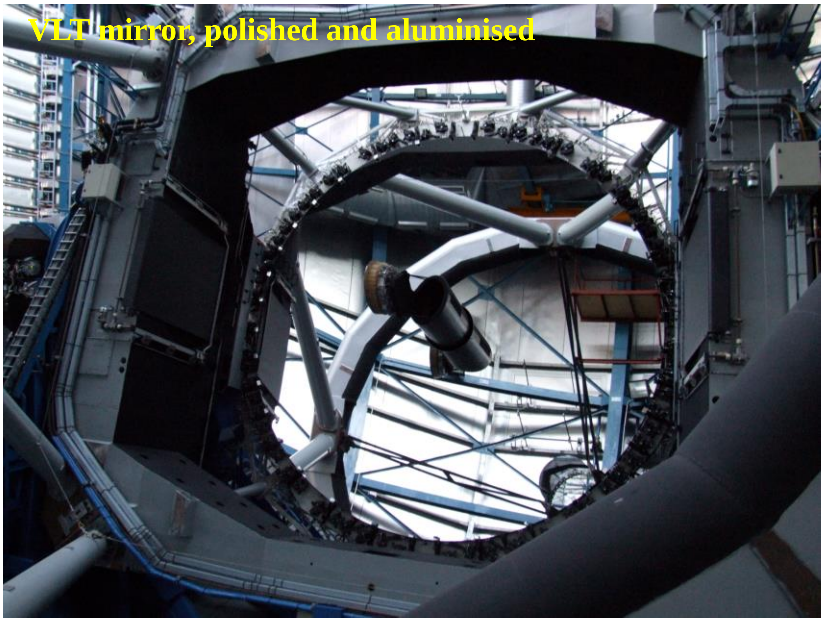
- 4x8.2m, (European Southern Observatory) at Paranal in northern Chile, plus smaller telescopes operating as an interferometer.

Currently largest telescope in the world

The Gemini Telescopes

2x8m, Hawaii and Chile.
UK is (at present) a member of the Gemini Consortium.

VLT mirror, polished and aluminised



Surface accuracy ~47nm RMS (ratio of 2.5 mm to distance from NY to LA!)

Very Large Array

High resolution radio maps via aperture synthesis Interferometry, a technique originally developed in Cambridge ~1960

The VLA Radio Telescope is situated in New Mexico,
USA

27 dishes, each 25m diameter.

Max baseline 21km, frequency 70 MHz to 50 GHz

The James Clerk Maxwell Telescope.

15m sub-mm telescope.

UK built, on Mauna Kea, Hawaii.

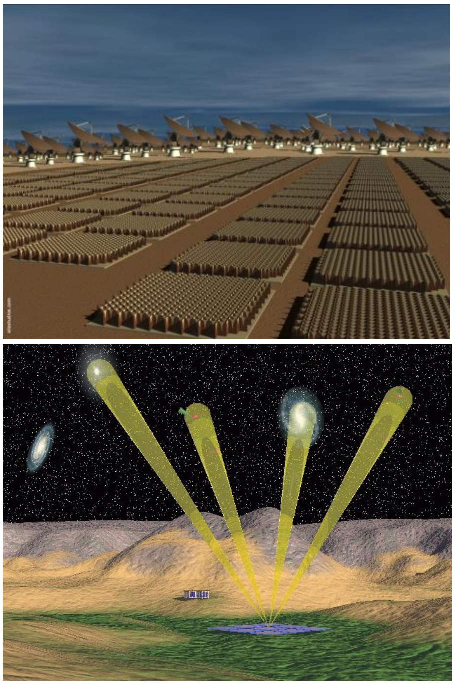
The Atacama Large Millimetre Array (ALMA)

The Atacama Large Millimetre Array (ALMA)

- 64, 12m sub-mm quality antennas, though this number is still being argued about!
- 30-950 GHz (300 - 1000 microns)
- Baselines up to 10km - high angular resolution
- High altitude site in the Atacama desert in northern Chile, 5000m.
- The ALMA correlator will perform 16,000 million-million (1.6×10^{16}) operations per second.
- This will give the spectral resolution of only 10 m per second.
- Low temperature BB, high z, obscured regions, molecular transitions
- Will study earliest and most distant galaxies and planet and star formation where very high redshifts push most of the emission into submillimetre bands.
- First "light" in 2010, now very productive with very high spectral resolution.
- Operated by ESO.

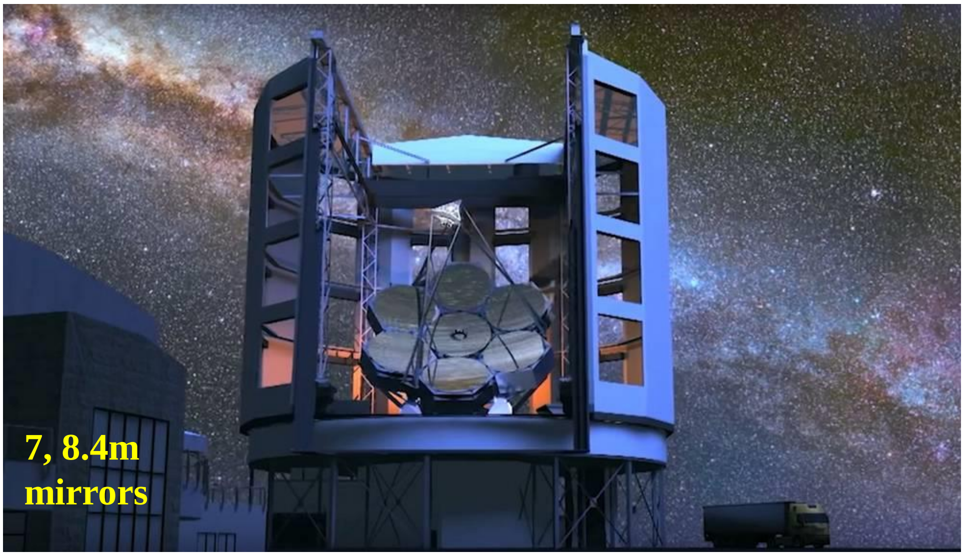
The Square Kilometre Array (SKA)

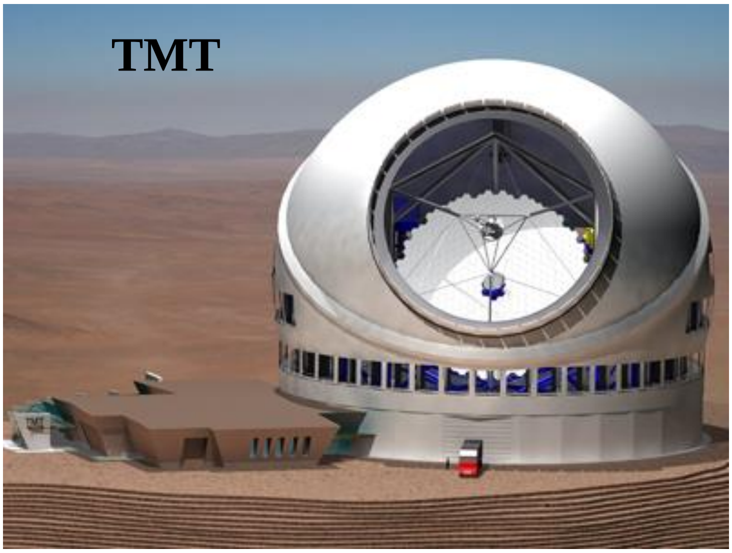
- This is a project for a 60MHz to 30 GHz radio array synthesis telescope.
- Uses a combination of steerable antennae and wide angle receivers with simultaneous multi-beam imaging capability.
- Will be fabulously expensive, with a lot of the cost going on integrated circuits to process the data.
- Handles 10^8 pixels, 10^4 spectral channels at several KHz, so 10^{13-14} bits/sec of data continuously. Hmmm….



Future Telescopes: The Giant Magellan Telescope

7 mirrors of 8.2m, equivalent to ~22m single mirror.
Targets first light in 2029. Located in Chile at Las Campanas.

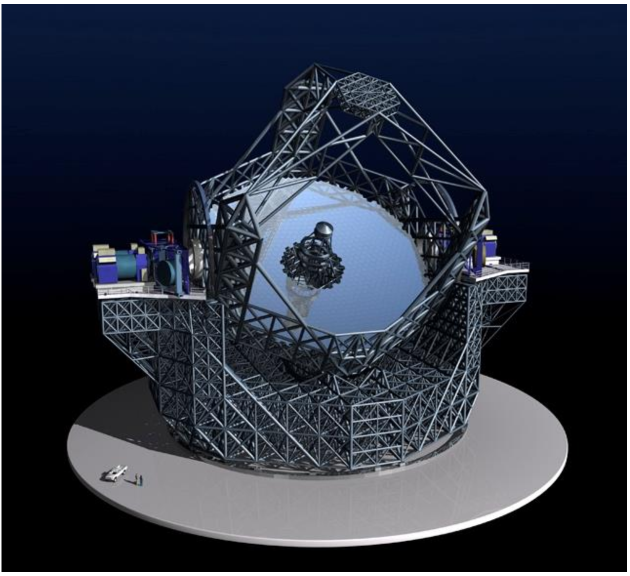




The Thirty Metre Telescope.
Proposed 30m telescope.
Maybe on Mauna Kea, or La Palma. Massive political problems.

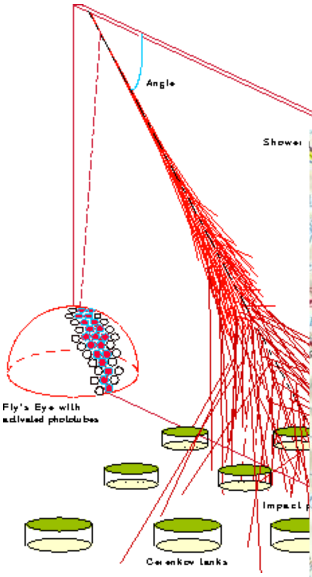
The European - Extremely Large Telescope (E-ELT).

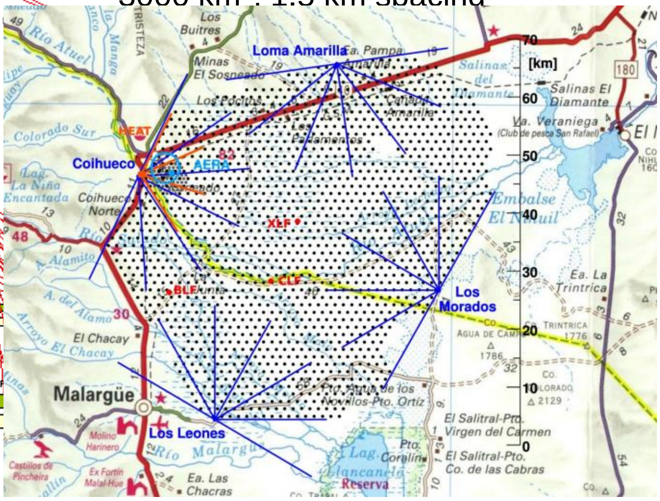
39m telescope, ESO at Cerro Armazones near Paranal.
Segmented mirror with extreme AO.
First light targeted in 2025.



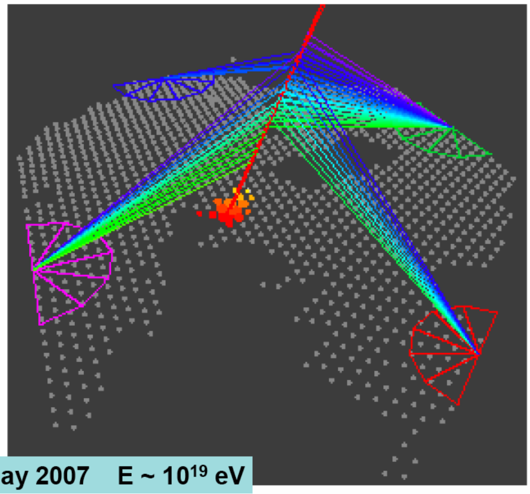
Detecting Ultra-High Energy Cosmic Rays with the Pierre Auger Observatory Malargue, Argentina

Surface tank array: 1600 tanks
3000 km^2; 1.5 km spacing

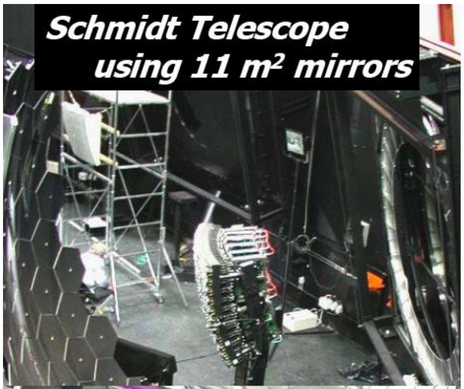




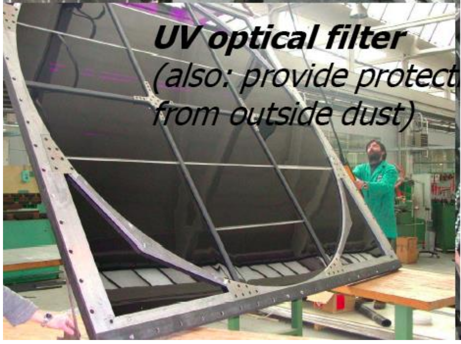
Event seen in 4 FD + ~15 SD



20 May 2007 E ~ 10^{19} eV



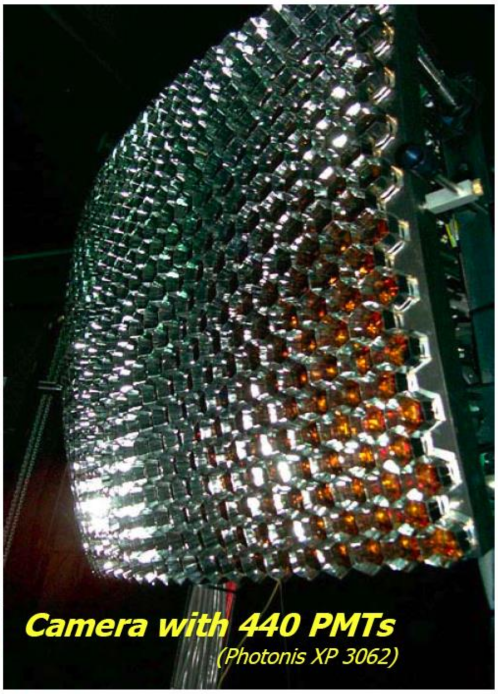
Schmidt Telescope using 11 m^2 mirrors



UV optical filter

(also: provide protect

from outside dust)

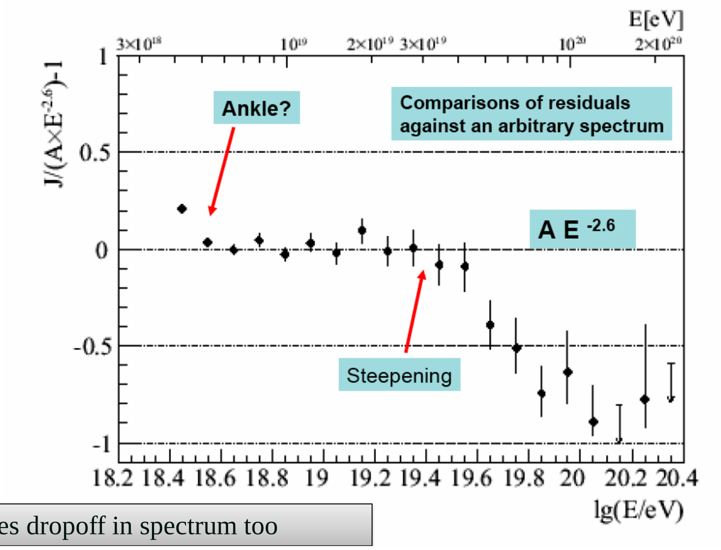


Camera with 440 PMTs

(Photonis XP 3062)

Auger Spectrum shows downturn consistent with GZK

(Greisen-Zatsepin-Kurmin: CRs +CMB> pions) limit or maybe sources just get tired…)



HiRes sees dropoff in spectrum too

Astronomical Instruments - 1

- Generally, an instrument is a box of tricks stuck on the back of a telescope.
- Consists of some optics which feed the light from the telescope focal plane to a detector, either directly for imaging applications or via a light analyser such as a spectrograph or a polarimeter.
- Should maximise the light from the target and minimise the light from spurious background sources.
- Instrumental efficiency is extremely important. If you can double the detection efficiency of your instrument it is equivalent to doubling the area of your telescope. As a consequence a lot of money is spent maximising instrumental performance.
- Typical cost is $5-15M for an instrument for an 8-m telescope, with much larger costs being anticipated for the yet bigger instruments needed for the next generation of very large telescopes.

Astronomical Instruments -2
Detectors

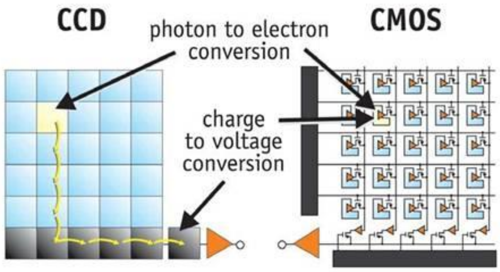
- Today almost all detection is done by semiconductor devices with millions of pixels.
- Charge Coupled Devices (CCDs) work in the range of 0.35-1.1 microns: the have high quantum efficiency (QE) of up to 95%, very low readout noise (the noise they produce in the absence of any input signal) and very large formats (4096x4096 pixels) in a single device.
- Their best performance is achieved by reading out relatively slowly (hundreds of kilohertz pixel rate)
- The largest imaging detectors use arrays of these devices. The largest arrays are now approaching one billion pixels each.
- There are now very fast (15-60 MHz) pixel rate CCDs that are virtually noise-free. At present they are only available in limited and relatively small device formats. They are capable of photon counting at high speed.
- Large detector arrays cannot effectively use shuttering so the image is transferred across the detector leading to image smearing that can compromise photometric performance.

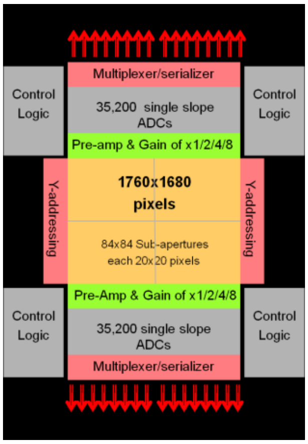
Astronomical Instruments -3
Detectors

- Commercially visible light detectors (mobile phones, WebCams, surveillance cameras etc) dominated by CMOS detectors (complementary metal-oxide-semiconductor).
- These work by transferring the accumulated signal within each pixel through a buffer amplifier to common video lines that are not light-sensitive. This eliminates image smearing.
- They are manufactured using standard microprocessor type technologies so can be made very cheaply and quickly. This allows for integrated readout electronics and massively parallel high-speed readouts.
- The main catches that designing these devices for astronomy can be very expensive.

- Near IR arrays (0.85-5.0 microns) nearly as good as CCDs in terms of quantum efficiency and general image quality. The largest are now 4096x4096 pixels.
- Further into the red detectors have fewer pixels, lower QE and more noise.

Astronomical Instruments -3 Detectors

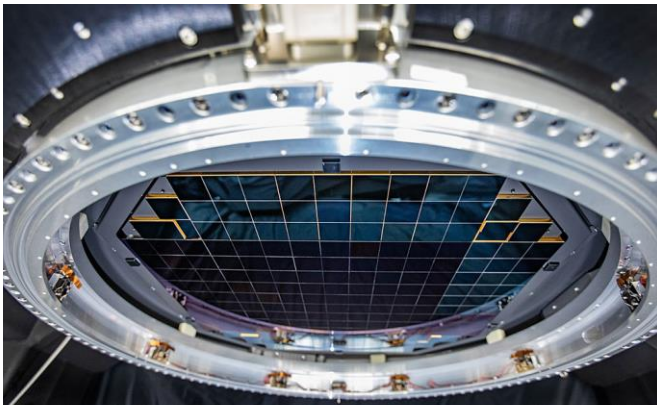


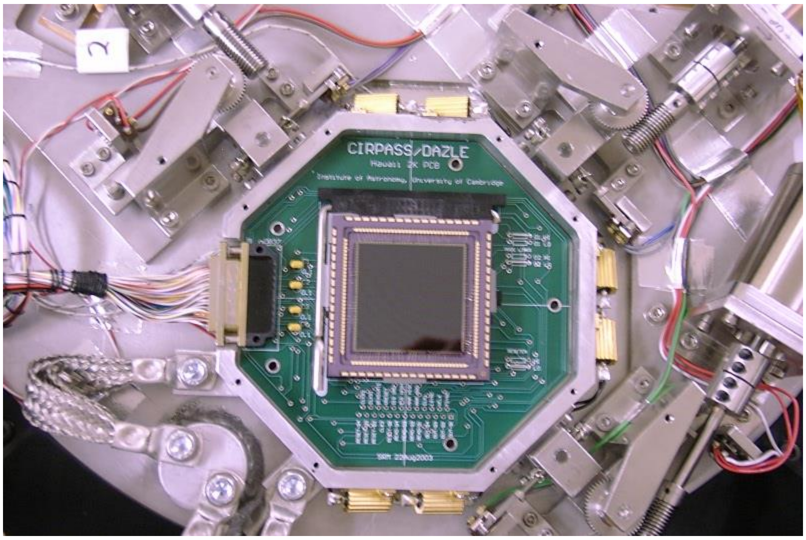


- The blue areas indicate light sensitivity.
- Although CMOS devices used a significant part of the pixel area for readout electronics.
- Today most detectors (both CCD and CMOS) are back illuminated to give very high effective quantum efficiencies, >95% in many cases.
- Astronomers very seldom use colour detectors. Filters are used to isolate individual bands and dichroics can allow multicolour imaging.

Large Area CCD Array

- This picture shows an array of 189 CCDs giving ~3.2 billion px.
- An array such as this will cost about $10 million.
- It is operated at a temperature of about -120C, in a vacuum dewar mounted on the telescope.
- Each CCD has four outputs and all 756 outputs are read in parallel.



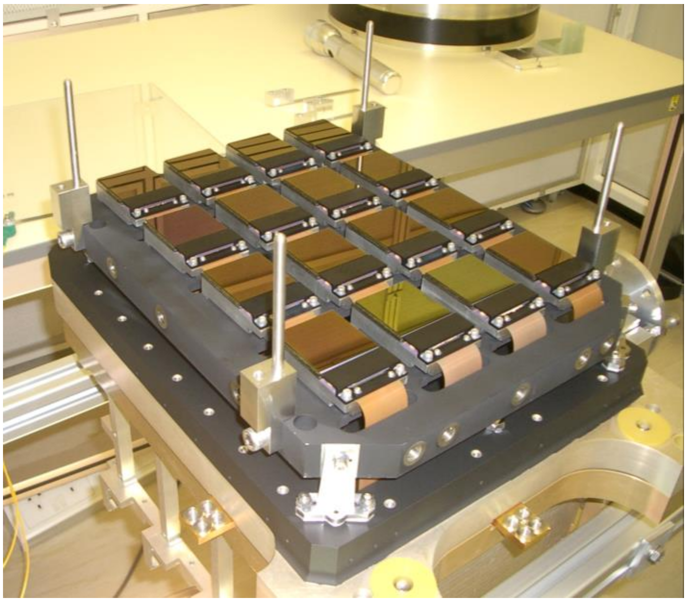


Hawaii-II 2048^2 IR Array

(0.85-2.5 microns)

VISTA, 4-metre survey telescope

4x4 detectors, each is 2048x2048 pixels, 0.9-2.5µm



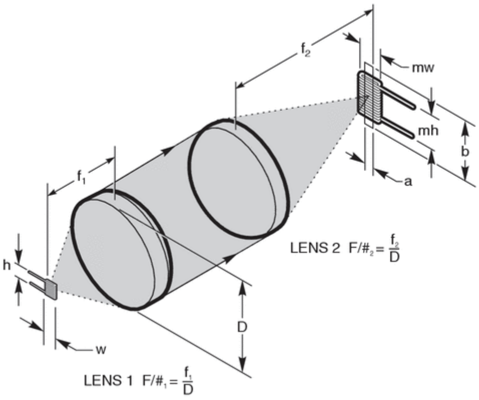
Astronomical Instruments: Imaging

Imaging instruments measure the various parameters about the radiation collected by the telescope. They measure:

- The various directions from which it came characterised by the instrumental angular resolution in arc seconds per pixel and the total field of view of the instrument.
- It measures the radiation at different wavelengths with different spectral resolutions and wavelength coverage.
- It also measures the radiation at different times, and the temporal resolution of the instrument may be important for some objects.
- All electromagnetic radiation can in principle be polarised and so the instrument may have the capacity to measure the different polarisation states.

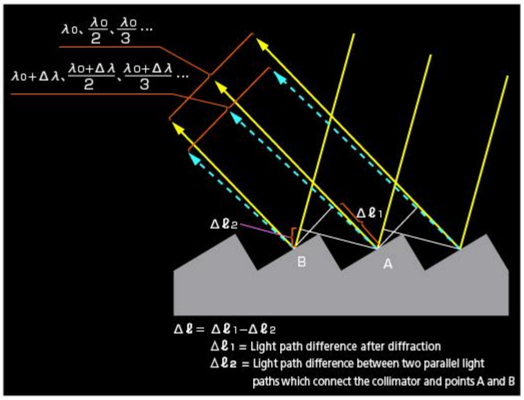
Astronomical Instruments: Imaging

- This picture shows how a reimaging system works.
- The input image on the left is magnified in proportion to the focal length ratios of the two lenses.
- The output image is magnified.
- Filters may be placed between the two lenses particularly if narrow passbands are being used where a parallel beam gives the best performance.



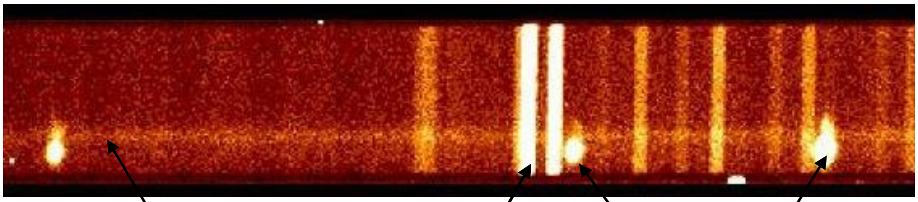
Astronomical Instruments: Spectrograph

- If we place a component that disperses the light according to its wavelength in the optical path of a camera then we have a spectrograph.
- This shows the way that diffraction gratings work.
- Beams of slightly different wavelength combined coherently in slightly different directions.



Principle of diffraction by the grating

Astronomical Instruments: Slit Spectrum



Continuum of galaxy

Night sky emission line

Galaxy emission lines

High-Quality, High Resolution Spectrum

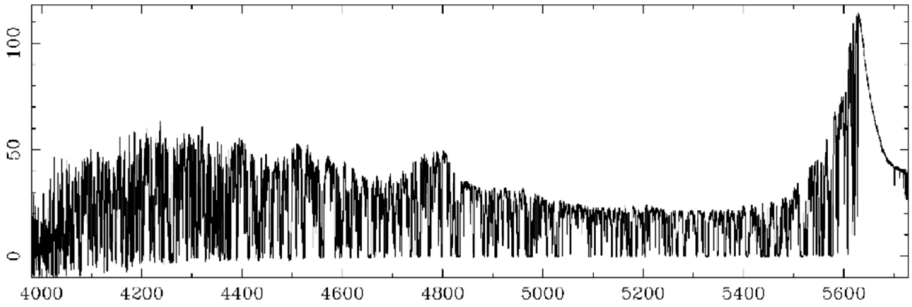
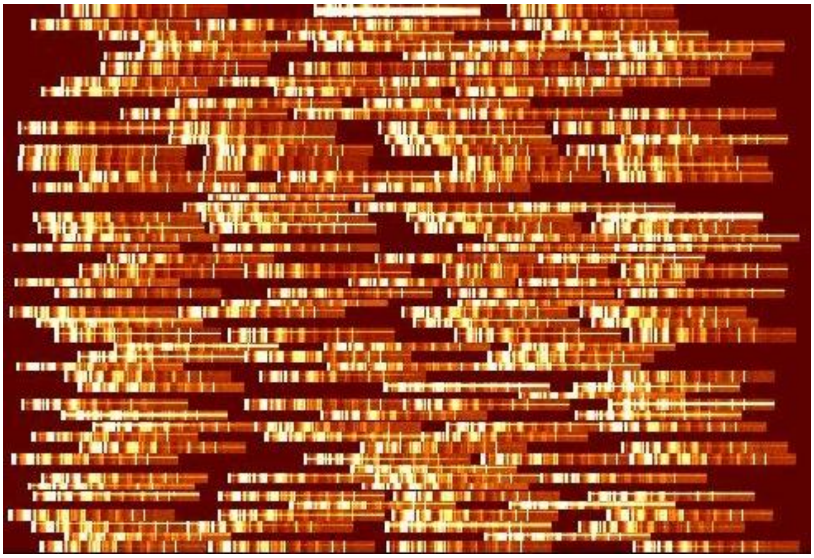


Figure 1 High resolution [full width at half maximum (FWHM) ≈ 6.6 km s^{-1}] spectrum of the $z_{em} = 3.62$ QSO1422+23 ($V = 16.5$), taken with the Keck High Resolution Spectrograph (HIRES) (signal-to-noise ratio ~150 per resolution element, exposure time 25,000 s). Data from Womble et al (1996).

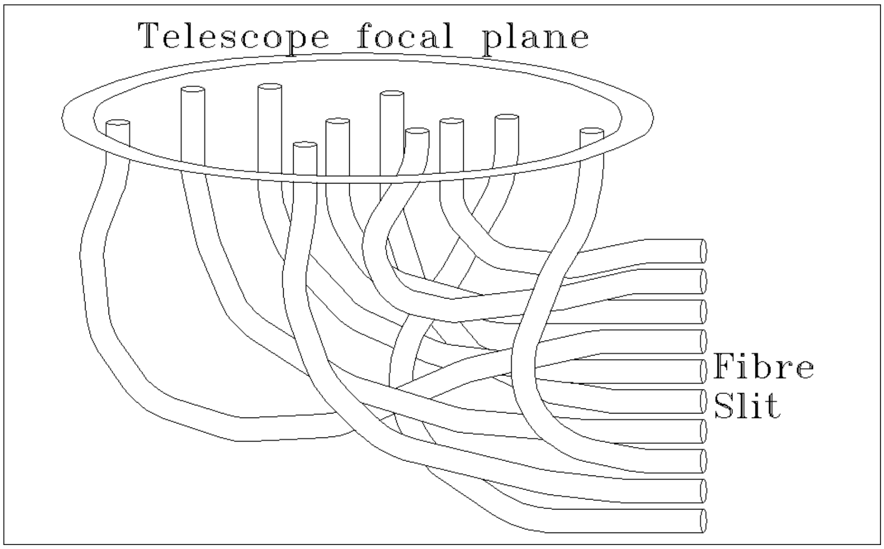
Multi-Object Spectroscopy

- By using many slits, instead of just one slit, it is possible to measure the spectrum of many stars or galaxies at the same time.
- An alternative method is to use optical fibres to “pipe” the light from the telescope focal plane to the spectrograph.

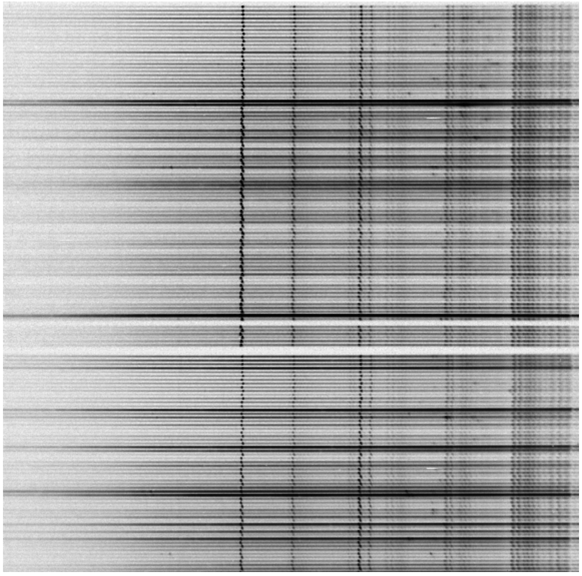
Multi-object spectroscopy using multi-slits



Multi-object spectroscopy with fibres

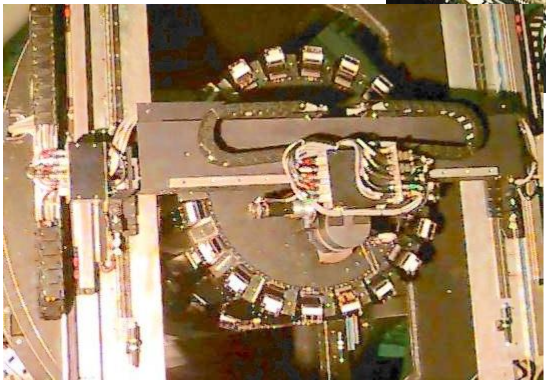


Multi-object spectroscopy using optical fibres



2dF Multi-Object Spectrometer.

(Anglo-Australian
Telescope.)

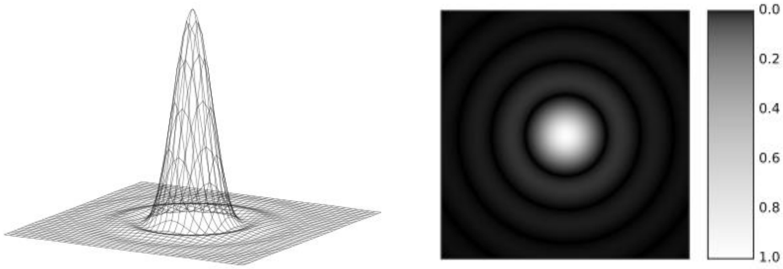


2dF=2 degree field
400 fibres
400 spectra

Diffraction pattern for a point source and a circular aperture

A second source on the first dark ring would be just resolved.
r=radius of first Airy ring (in radians), D=diameter of telescope,
λ=wavelength of light

$$r = 1.22\frac{\lambda}{D}$$



Diffraction pattern for a point source and a circular aperture

A second source on the first dark ring would be just resolved.
r=radius of first Airy ring (in radians), D=diameter of telescope,
λ=wavelength of light

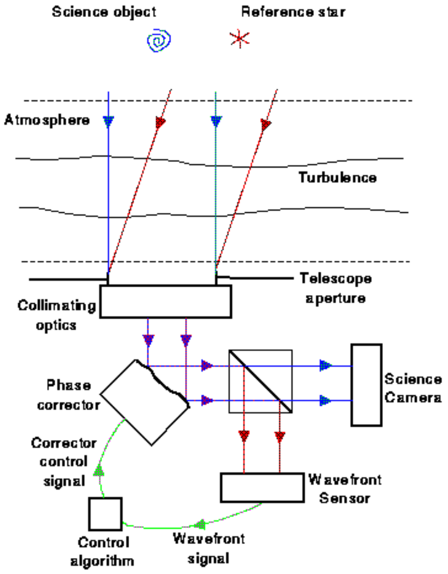
Example 1 (4-inch telescope):
D = 100 mm = 100,000 microns
λ= 0.55 microns = 550 nm
r = 1.4 arcsec

Example 2 (HST, visible light):
D = 2.5 m = 2.5×10^6 microns
λ= 0.55 microns = 550 nm
r = 56 milli-arcsec (but detectors undersample this, so r~100 mas in practice.

Example 3 (Keck Telescope, K-band):
D = 10 m = 10^7 microns
λ= 2.2 microns
r = 56 milli-arcsec (but not in practice!)

The Need for Adaptive Optics

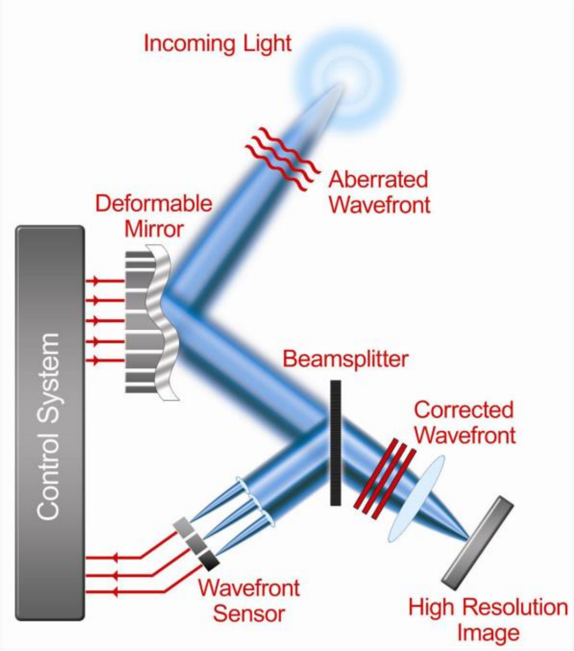
- The flat wavefront entering the top of the atmosphere is distorted by atmospheric turbulence on scales as small as 10 cm, and timescales of 10 ms typically.
- Adaptive optics is a technical attempt to correct for this by using a nearby reference star to allow the atmospheric errors to be measured and corrected for.
- Many problems exist but given that Hubble will not last for ever, astronomical instrument builders really have to do something!



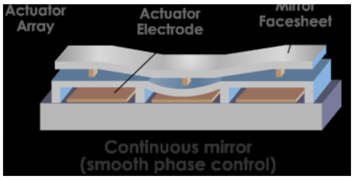
Adaptive Optics Principles

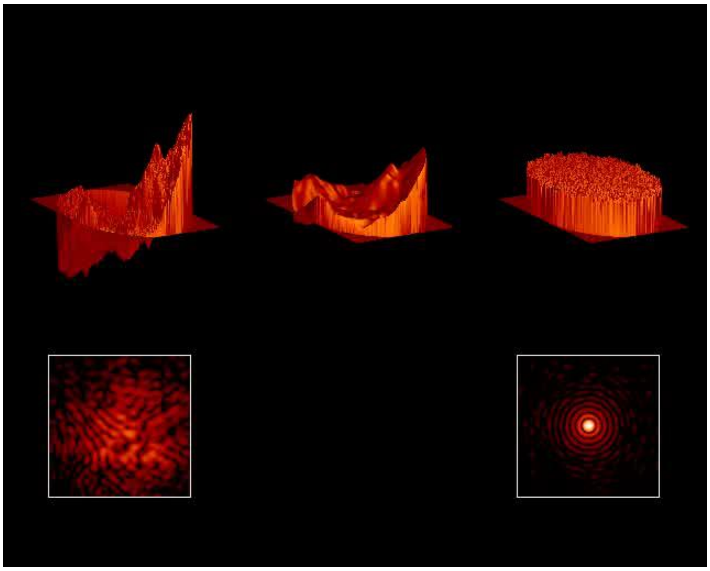
- Use a bright guide star (point source) to measure the wave-front distortion due to the atmosphere.
- Use this information to distort a flexible mirror in the AO system so that atmospheric distortion is cancelled out.
- Measurement and correction have to be done in a few milli-seconds before the atmosphere changes.
- The light in one passband is used to measure the distortion and the light in another is corrected.
- Problems include the fact that there are discontinuities in the phase that makes it impossible to follow precisely with a flexible mirror.
- Natural guide stars that are bright enough for this technique are few and far between so that very little of the sky can be imaged in this way.
- One solution is to use laser guide stars where sodium atoms at 25 km altitude are excited to produce artificial stars. Unfortunately they are not very compact and are created by light that has also passed through the same yet slightly different turbulent atmosphere.

Adaptive Optics General Scheme



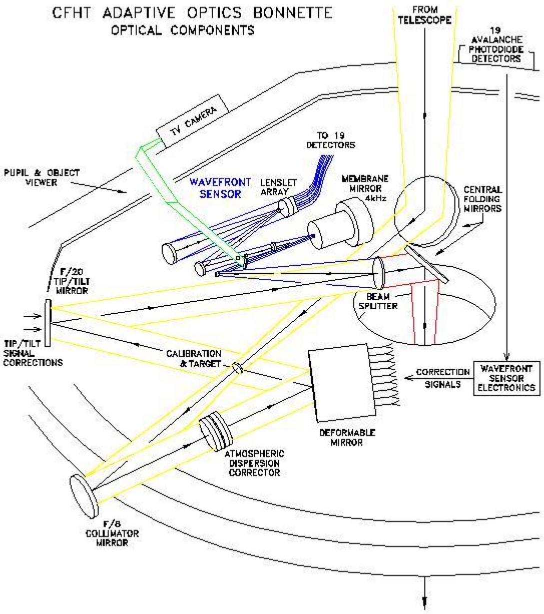
- A wavefront sensor measures the errors.
- A control system works out the correctiones needed.
- These are applied to a deformable mirror (hopefully) before the distortions change.
- MEMS deflectors used to distort the flexible mirror.



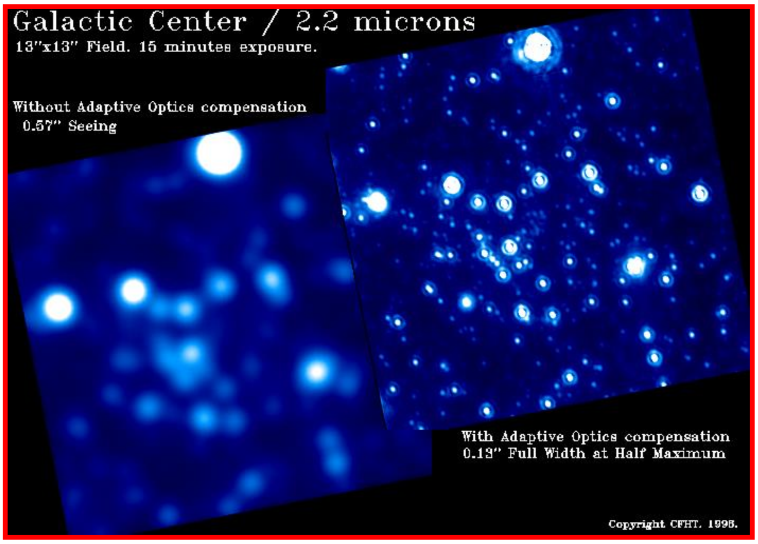


US Air Force (Maui) telescope, high-order AO system, Courtesy of Ben Oppenheimer, American Museum of Natural History, NY

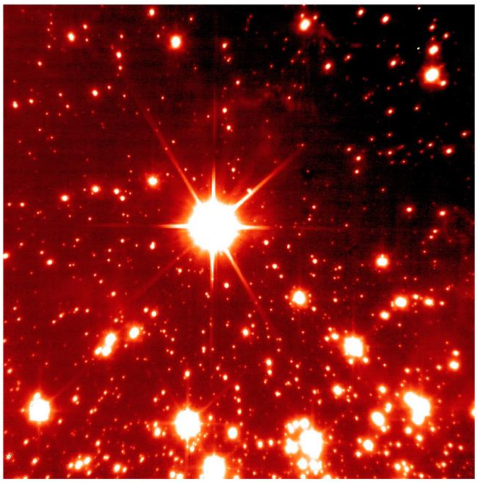
The AO system on the Canada France Hawaii Telescope



But the images are very pretty indeed under the right circumstances



But the images are very pretty indeed under the right circumstances:



Area Near Centre of NGC 3603
(VLT YEPUN + NAOS-CONICA)

ESO PR Photo 33c/01 (3 December 2001)

© European Southern Observatory

- This is a picture of a rich star cluster taken with an adaptive optics system in Chile.
- It uses the very bright central star to help it sort out the distortions produced by the atmosphere.
- One major problem is that the image shapes vary very rapidly with distance from the central reference star making it hard to compare the real properties of adjacent objects.

What Can We Do Already?

- Adaptive Optics is now working reasonably well in the near infrared but no one has produced Hubble resolution pictures in the visible from the ground routinely, far less near-diffraction limited imaging on 8 m class telescopes.
- AO systems have big problems addressing the non-Kolmogorov aspects of astronomical turbulence (intermittency effects: see Tubbs, Proc SPIE vol. 6272 pp 93, 2006)
- Laser guide stars will struggle to deliver resolution better than 0.1 times natural seeing.
- If we want to get adaptive optic systems to work with much fainter reference stars then we need to be a bit more cunning about what we might do.
- We start by thinking of the relative power when we analyse the turbulent spectrum in Zernicke terms.

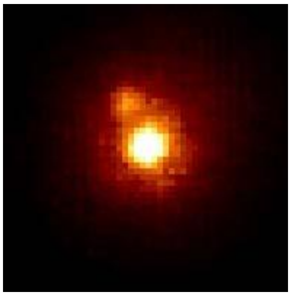
Table 1: the Zernike power spectrum of atmospheric turbulence (after Noll, 1976).

Zernike Terms Removed	Power in Each Zernike Term	Residual Power Fraction
1	0.0	1.0
2	0.435	0.565
3	0.435	0.130
4	0.022	0.108
5	0.022	0.085
6	0.006	0.063
7	0.006	0.057
8	0.006	0.051
9	0.006	0.045
10	0.006	0.039
11	0.0025	0.037
12	0.0025	0.034

- What we see is that the power is dominated by that in the lowest order (2 and 3 are simple tip-tilt).
- Removing them reduces turbulent residuals by ~87%.
- This is basis for Lucky Imaging.
- Removing simple defocus (4 and 5) reduces residuals to <1%.

Lucky Imaging.

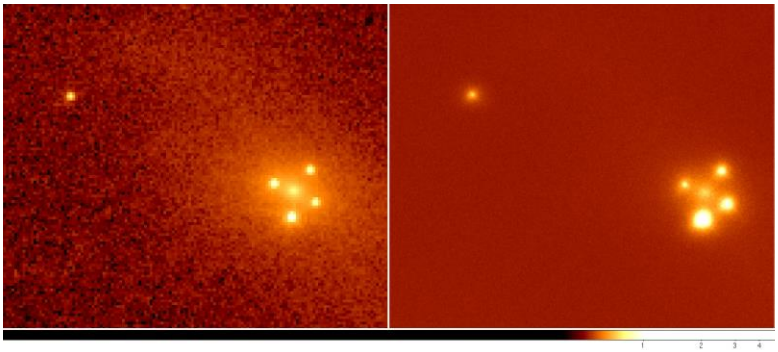
- Lucky Imaging uses high-speed noiseless EMCCD cameras to freeze image motion due to atmospheric turbulence. A reference star in the field allows the sharpest images to be selected, then shifted and added to produce an output image.
- On 2.5 m class telescopes in I-band (850 nm) selecting 5-30% of the images gives a resolution of 0.1-0.15 arcsec.
- We are therefore able to achieve near Hubble resolution routinely in the visible. Science targets can be very faint indeed (I > 25 mag).



0.12 arcsec binary, Δ_{mag} ~ 2.5 imaged with LuckyCam on the NOT 2.5m telescope (June 2005)

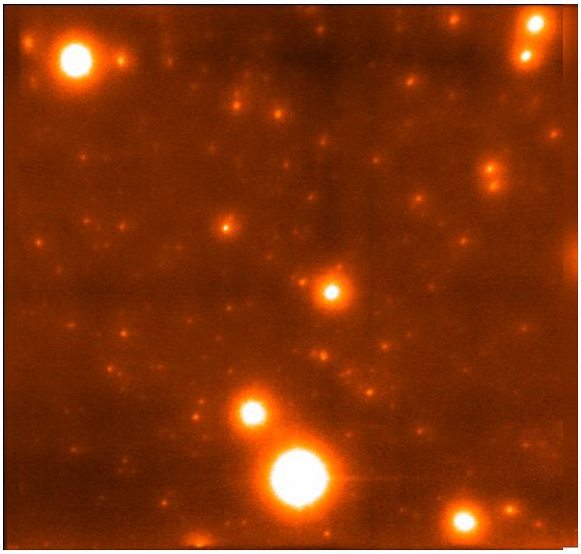
What Can We Do Already?

- Einstein Cross Gravitational Lens. HST (left), Lucky on the right.
- Resolution with Lucky on 2.5m is better than Hubble as HST is significantly undersampled.
- The lens components change relative brightness on short time scales (months>>years) because of microlensing by objects in the core of the lensing galaxy.



Large Telescope Lucky Imaging.

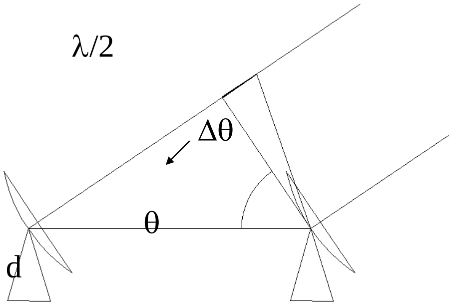
- Globular cluster M13 on the Palomar 5m.
- Natural seeing ~ 650 mas.
- Imaged via the PALMAO system and our EMCCD Lucky Camera.
- Achieved 17% Strehl ratio in I-band, giving ~35 mas resolution.
- This is the highest resolution wide-field image ever taken in the visible/I-R from space or from the ground.



Resolution of a Radio Interferometer

Constructive interference at θ
Destructive interference at θ+Δθ

$$\Delta\theta = \frac{\lambda/2}{d\cos\theta} \sim \frac{\lambda}{d}$$



Resolution of a Radio Interferometer

Example 4 (VLA radio telescope):
d = 27 km
λ= 21 cm
$\Delta\theta$ = 1.6 arcsec

Example 5 (Very Long Baseline Interferometry - VLBI):
d = 10,000 km
λ= 10cm (radio wavelength)
$\Delta\theta$ = 0.2 milli-arcsec

Example 6 (Jodrell Bank, Lovell dish):
d = 76 m = 10^7 microns
λ= 13.6 cm (22GHz water)
$\Delta\theta$ = 37 arcsec

Example 7 (VLT Optical Interferometer):
d = 200 m
λ= 2.2 microns (K-band infra red)
$\Delta\theta$ = 2.2 milli-arcsec

The accuracy of measuring the brightness of a star

- We feed the light from the star on to a detector. In addition to the star light we also detect an unwanted background signal.
- We therefore take 2 measurements: one of the star plus the background and one just of the background so we can subtract it off.
- The first measurement is $[Q+B_1]$ and the second is $[B_2]$ where B_1 and B_2 are the contributions from the background and Q is the signal from the star. The exposure time, T, is the same in both cases.
- To estimate Q we assume $B_1=B_2=B$. $Q=[Q+B]-[B]$
- The error in this estimate is the error of the 2 measurements added in quadrature.
- Assume the measurements are in photons which obey Poisson statistics such that for N photons

$$error=\sqrt{N}$$

- The error in our estimate of Q is therefore $\sqrt{\left(\sqrt{Q+B}\right)^2+\left(\sqrt{B}\right)^2}=\sqrt{Q+2B}$
- The signal-to-noise ratio, Z, is then given by $\frac{S}{N}=Z=\frac{Q}{\sqrt{Q+2B}}$

The accuracy of measuring the brightness of a star

- Introduce the photon rates R_Q from the star and R_B from the background such that in exposure time T we have

$$Q = R_Q T, \qquad B = R_B T$$

- The expression for Z can be written

$$Z = \frac{R_Q T}{\sqrt{R_Q T + 2 R_B T}}$$

$$Z = \sqrt{T}\,\frac{R_Q}{\sqrt{R_Q + 2R_B}}$$

- Solving this for T we get

$$T = \frac{Z^2\left(R_Q + 2R_B\right)}{R_Q{}^2}$$

- To double the Signal to Noise Ratio we must quadruple the exposure time.