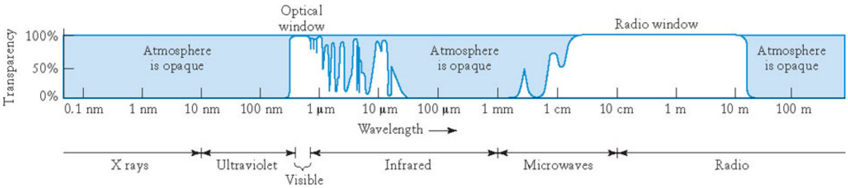
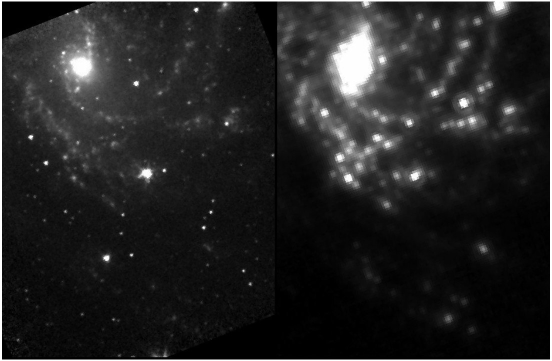
Beyond optical



Mirrors at other wavelengths

- For a given mirror size, optical performance gets worse at longer wavelengths. (Θ=2.5$\times$10^{-4}λ/D)

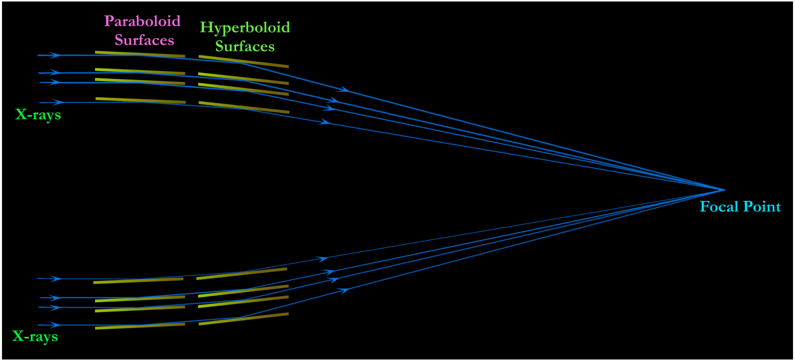


Mirrors at other wavelengths

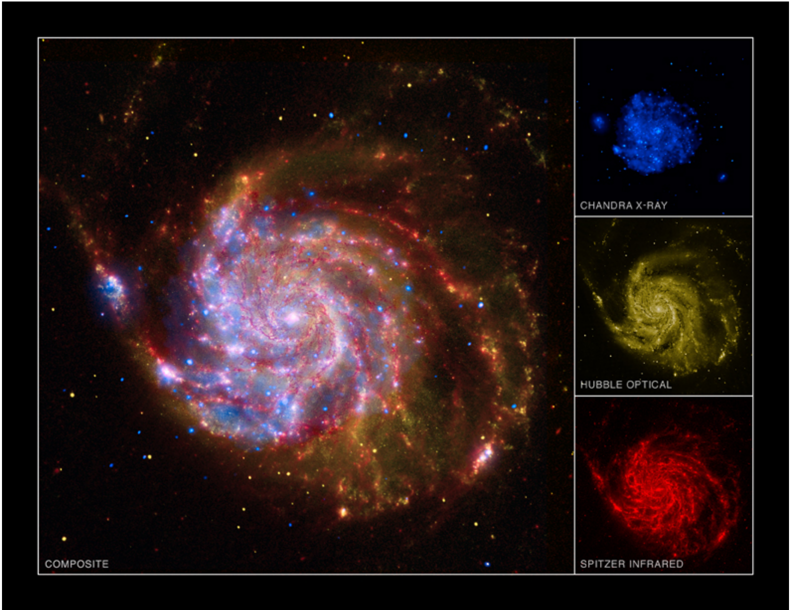
- But, although you need a larger mirror at longer wavelengths, the mirror does not have to be so finely made.
- Surfaces need to be polished to within 1/20th of a wavelength of the required shaped. This is pretty hard for optical (500nm) but much easier for radio ($>$1cm). Radio telescopes are much easier to make than optical telescopes.

Mirrors at other wavelengths

- Mirrors at very short wavelengths are tricky, because X-rays and gamma rays can penetrate the mirror, if they fall directly on it. Instead, grazing incidence mirrors are used.



Chandra X-ray observatory



Chandra X-ray observatory

Radio telescopes

- We saw earlier that the resolution limit of a telescope is given by $\Theta = 2.5\times10^{-4}\ \lambda/D$
- Radio wavelengths are about 100,000 - 1,000,000 times longer than optical wavelengths, so to achieve the same resolution, you would need a telescope at least a hundred thousand times larger.
- The largest radio telescope is Arecibo, with a dish 305m across. This is pretty huge, but it's only 30 times as large as the largest optical telescope. You really need a telescope tens of kilometres across.

Radio telescopes

Radio telescopes

Interferometry

- Resolution is thus a major problem in radio astronomy. To overcome this, the technique of interferometry was developed.
- By observing an object with two or more very widely spaced telescopes, you are effectively observing them with a mirror with a diameter equal to the separation of the telescopes.
- Combining the signals is very complex, and you have to know the distance between the telescopes very precisely, but the technique is very refined, and in fact, the resolution that is possible with interferometry is much better than optical telescopes can do.

Interferometry

- The Very Large Array is a single-site interferometric array, in New Mexico. 27 dishes in a Y configuration can cover an area 27km across, and can achieve a resolution of 0.05 arcseconds.

Interferometry

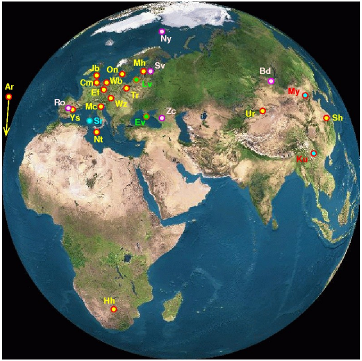
Animation - available in screen version

Very Long Baseline Interferometry

- Still better resolution is possible with Very Long Baseline Interferometry (VLBI).
- In the UK, the Multi-Element Radio Linked Interferometer Network (MERLIN) consists of 7 radio telescopes across the UK (including Jodrell Bank), separated by up to 217km. Its resolution is significantly better than the VLA.

Very Long Baseline Interferometry

- MERLIN can also act as part of the European Very Long Baseline Network (EVN), and the EVN can also observe at the same time as the Very Long Baseline Array (VLBA) in the US.

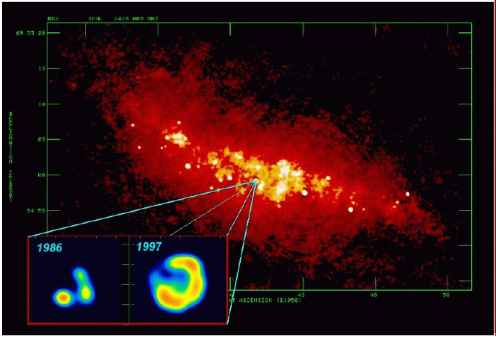


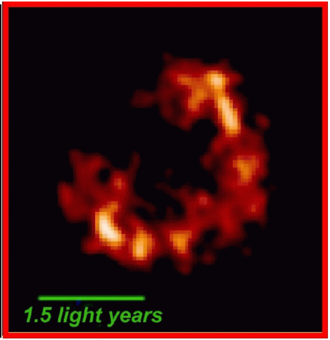
Very Long Baseline Interferometry

- And... the EVN + VLBA can even operate with space-based radio telescopes, giving an effective aperture of 20,000km! This gives resolutions of just micro-arcseconds. (something 1mm across on the surface of the moon would have an angular size of 1 micro-arcsecond!)

Very Long Baseline Interferometry

- The expanding remnant of an exploding star, 12 million light years away - LH image shows galaxy M82 observed with MERLIN+VLA; lower two insets are EVN; right hand image is global - EVN+VLBA



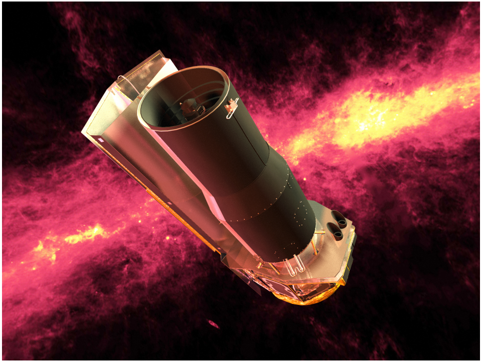


Infrared astronomy

- The atmosphere absorbs strongly at many infrared wavelengths (this is what gives rise to the greenhouse effect). This makes observing infrared radiation from the ground quite difficult.
- Water vapour accounts for about 75% of the absorption, so observing is possible, if you go somewhere dry enough, or high enough (because water vapour is strongly concentrated in the lower parts of the atmosphere).
- Mauna Kea, at 4200m above sea level, is a good place to observe from, as is the Atacama desert in South America, and Antarctica.

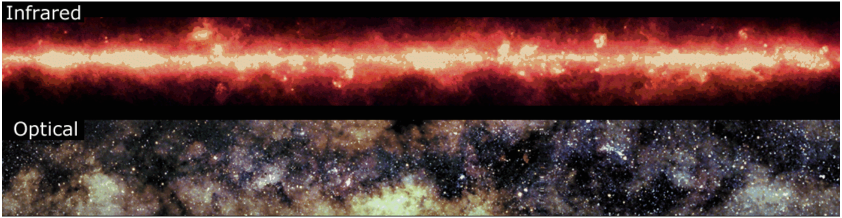
Infrared astronomy

- Observing in Antarctica would also go some way towards solving the other problem with IR astronomy – the equipment itself radiates strongly at IR wavelengths.
- So, telescopes and detectors need to be cooled to reduce their IR emission.

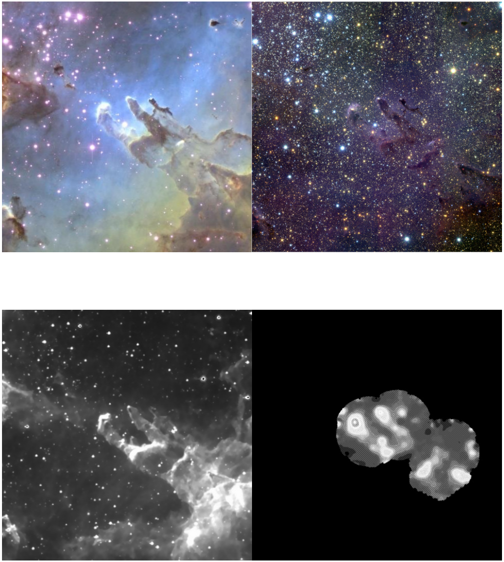


Infrared astronomy

- Why observe in the infrared?
- Cold things emit in the IR - and also things that strongly absorb visible light are transparent to IR.

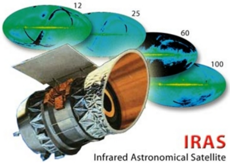


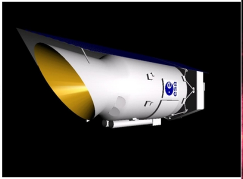
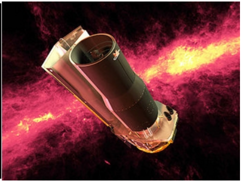
Infrared astronomy



Infrared space observatories

- Infrared space telescopes have included IRAS in the 1980s, ISO in the 1990s, and Spitzer in the 2000s. All had 60-85cm mirrors.



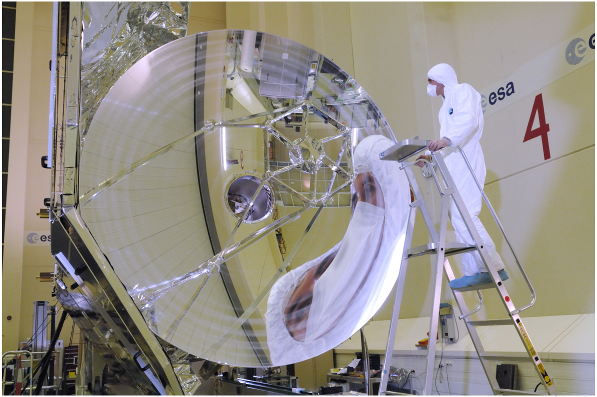



Infrared space observatories

- BLAST: Balloon-borne Large Aperture Submillimetre Telescope.
- Pathfinder for Herschel - same instruments, smaller mirror, missions in cold environments

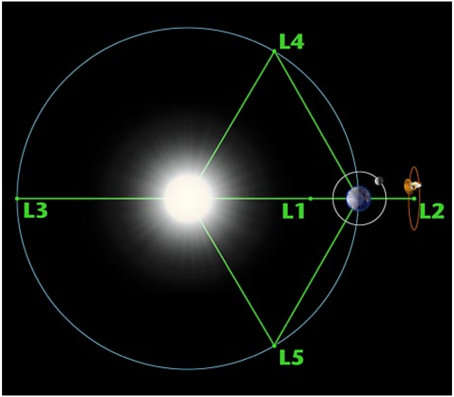
Infrared space observatories

- Herschel - planned since 1982, originally called the Far InfraRed Space Telescope - FIRST
- Named Herschel in 2000.
- Herschel has the largest mirror yet put into space - 3.5m across



Infrared space observatories

- Herschel was launched successfully on 14 May 2009. Unlike Hubble it is not orbiting the Earth and cannot be repaired. It is orbiting the sun at a place called L2.



Herschel

- Two satellites were launched at the same time, to save money... and double the risk

Animation - available in screen version

Herschel

- Like other infrared telescopes, Herschel is cooled to $\sim$4K (-269^{o}C) by tanks of liquid helium. The helium evaporating cools down the telescope. This limits the lifetime of the instrument – no more helium = no more IR observations.
- The James Webb Space Telescope, successor to Hubble, will have a large sun shield to allow it to reach very cold temperatures without the need for liquid helium.
- Will be launched in 2014. Or maybe 2020...

Herschel

- CW Leo - brightest object outside solar system at 10μm

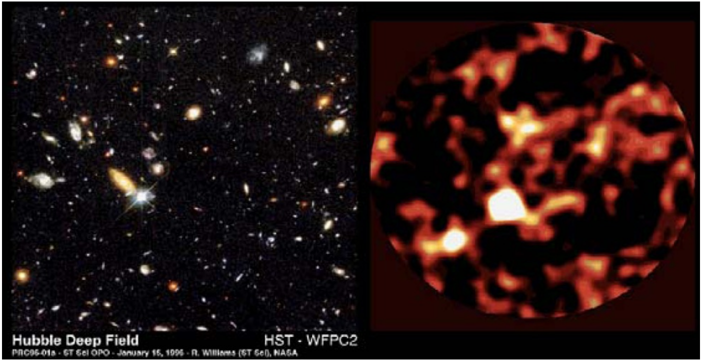
animation available in screen version

- Stars like this have carbon-rich atmosphere, but CW Leo has masses of water surrounding it.
- Herschel shows that it's the light from other stars that creates it

Herschel

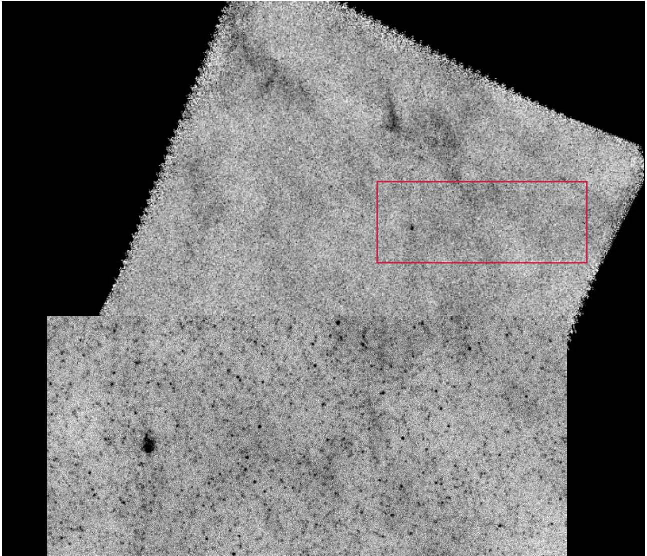
Herschel

- Hubble Deep Field was a landmark observation
- At submillimetre wavelengths, instruments on the James Clerk Maxwell Telescope in Hawaii observed for 20 nights and detected 5 sources.



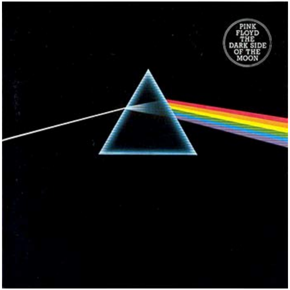
Herschel

- Herschel observed for 16 hours and detected 15,000 sources!



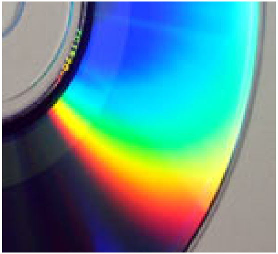
Spectrographs

- We've talked a lot about spectra, but not said anything yet about how they are obtained.
- Newton did a little bit of early spectroscopy, using prisms. But prisms have some of the same inherent disadvantages as refracting telescopes - they absorb light and need to be of very high quality.



Spectrographs

- A better way is to use *gratings*. You can see how gratings work if you hold a CD or DVD at an angle to a source of light. The fine rulings on the surface reflect and *diffract* the light, and different wavelengths are diffracted by different amounts.



- Gratings can disperse the light much much more than prisms can, so you can study objects in much more fine detail.

Spectrographs

- There is always a trade-off with spectrographs. The more you disperse the light, the longer your exposure needs to be to detect it.
- Ultra-high resolution spectroscopy can detect motions equivalent to walking pace from the Doppler effect.
- The first extra-solar planet was discovered with a spectrograph that could measure velocities of 7m/s - about the speed of a runner on a four minute mile.