Modern Astronomy:
An Introduction to Astronomy

Presented by
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School of Physics

Spring 2015

THE UNIVERSITY OF SYDNEY

This course is an introduction to modern astronomy, showing what we know about our place in the Universe and how we know it.

1. The Universe: a guided tour
2. The Sun and planets
3. The birth of stars
4. The evolution of stars
5. Stellar graveyards: white dwarfs, neutron stars and black holes
6. Miscellany: Binaries, clusters and variables
7. Our galaxy: putting the pieces together
8. Galaxies: normal galaxies to quasars
9. Cosmology: the universe as a whole
10. Modern astronomy: exoplanets, the "new astronomies", dark energy...

There will be an evening of star viewing in the Blue Mountains, run by A/Prof John O'Byrne on

Saturday 7 November

Details of where to go and how to get there are in a separate handout.

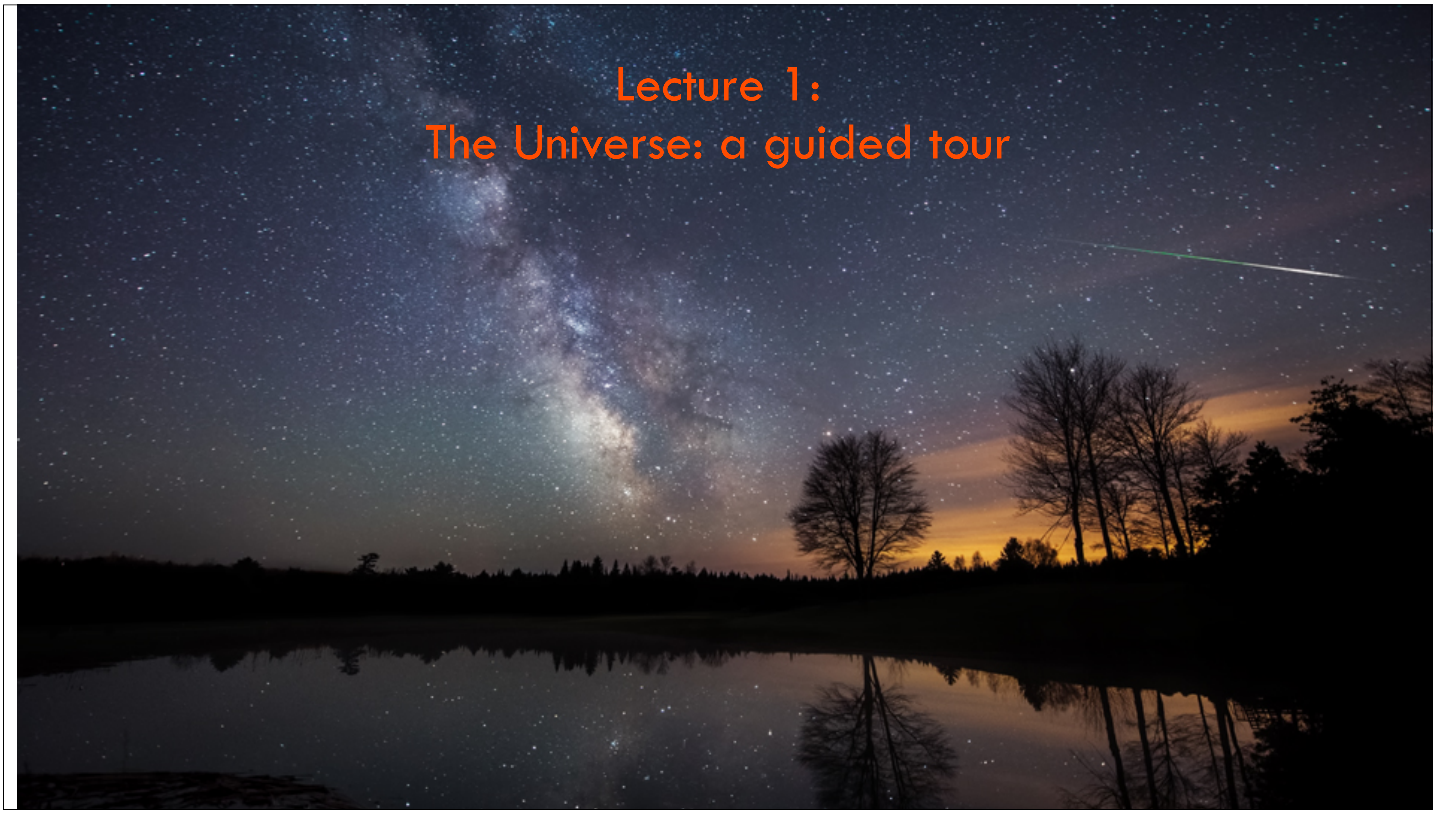
There is a course web site, at

http://physics.usyd.edu.au/~helenj/IntroductiontoAstronomy.html

where I will put

- PDF copies of the lectures as I give them
- lecture recordings
- copies of animations
- links to useful sites

Please let me know of any problems!



In tonight's lecture

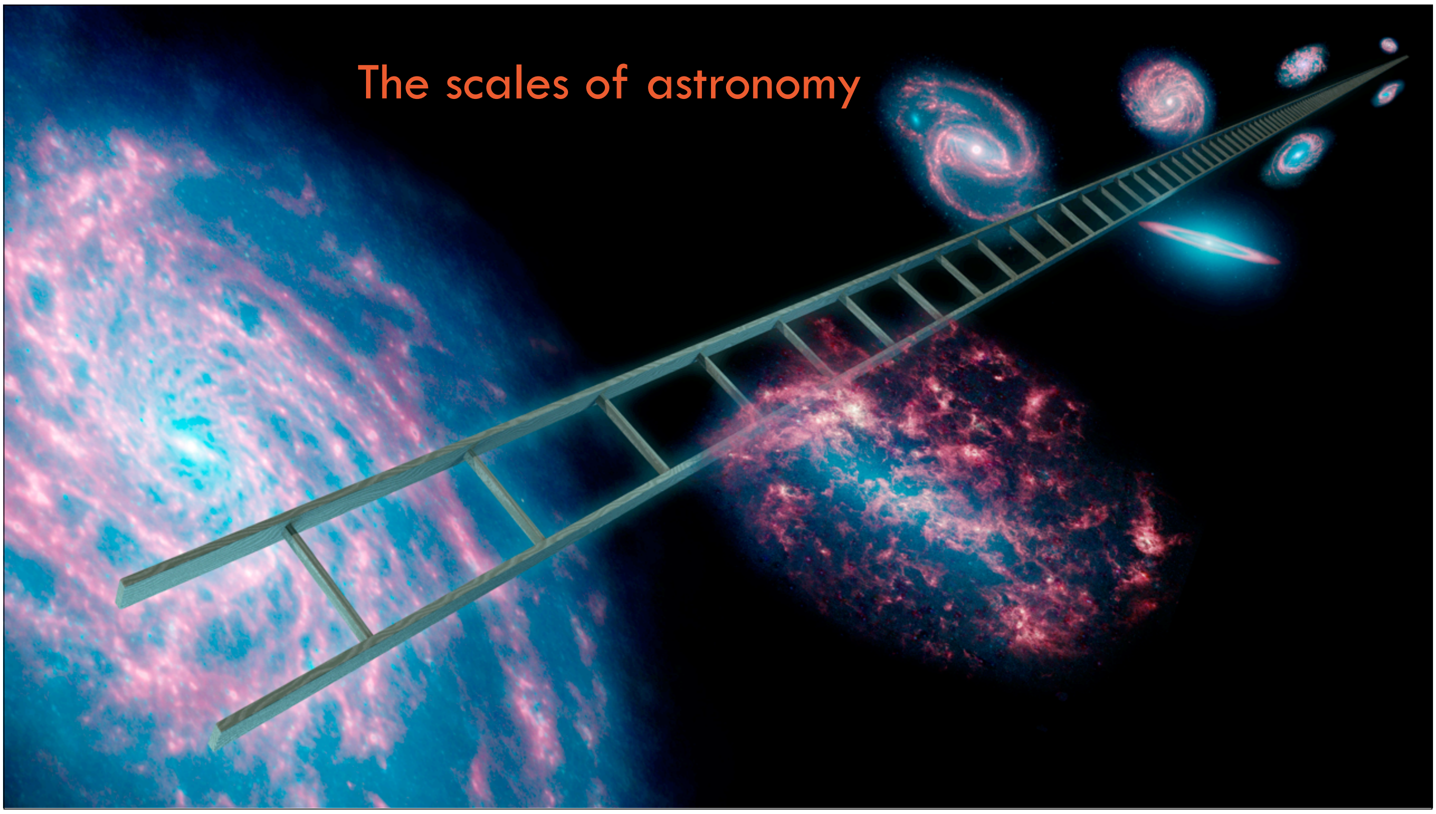
- A quick tour
  – *set the scene of where we are*
- The scales of astronomy
  – *just how big is the universe?*
- Electromagnetic radiation
  – *how do we find out about the universe?*

A quick tour

We are on a small planet orbiting with eight other planets and a host of smaller bodies around a medium-size orange-yellow star, which was born out of the interstellar gas about 5 billion years ago in a young cluster of stars.

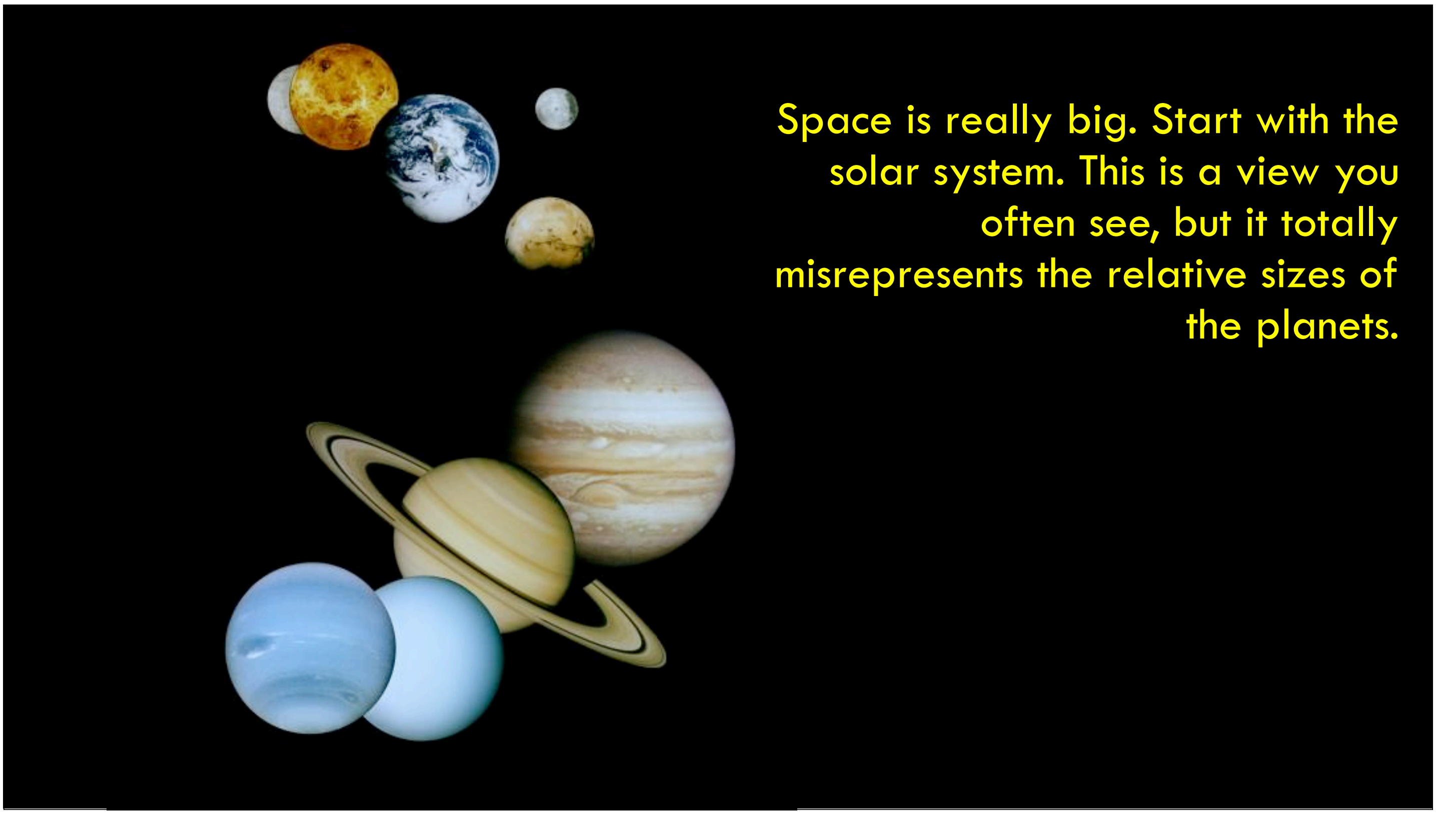
Our Sun will eventually expire in a fiery conflagration, spilling its gas back into interstellar space, leaving only a white dwarf behind, doomed to cool slowly into a

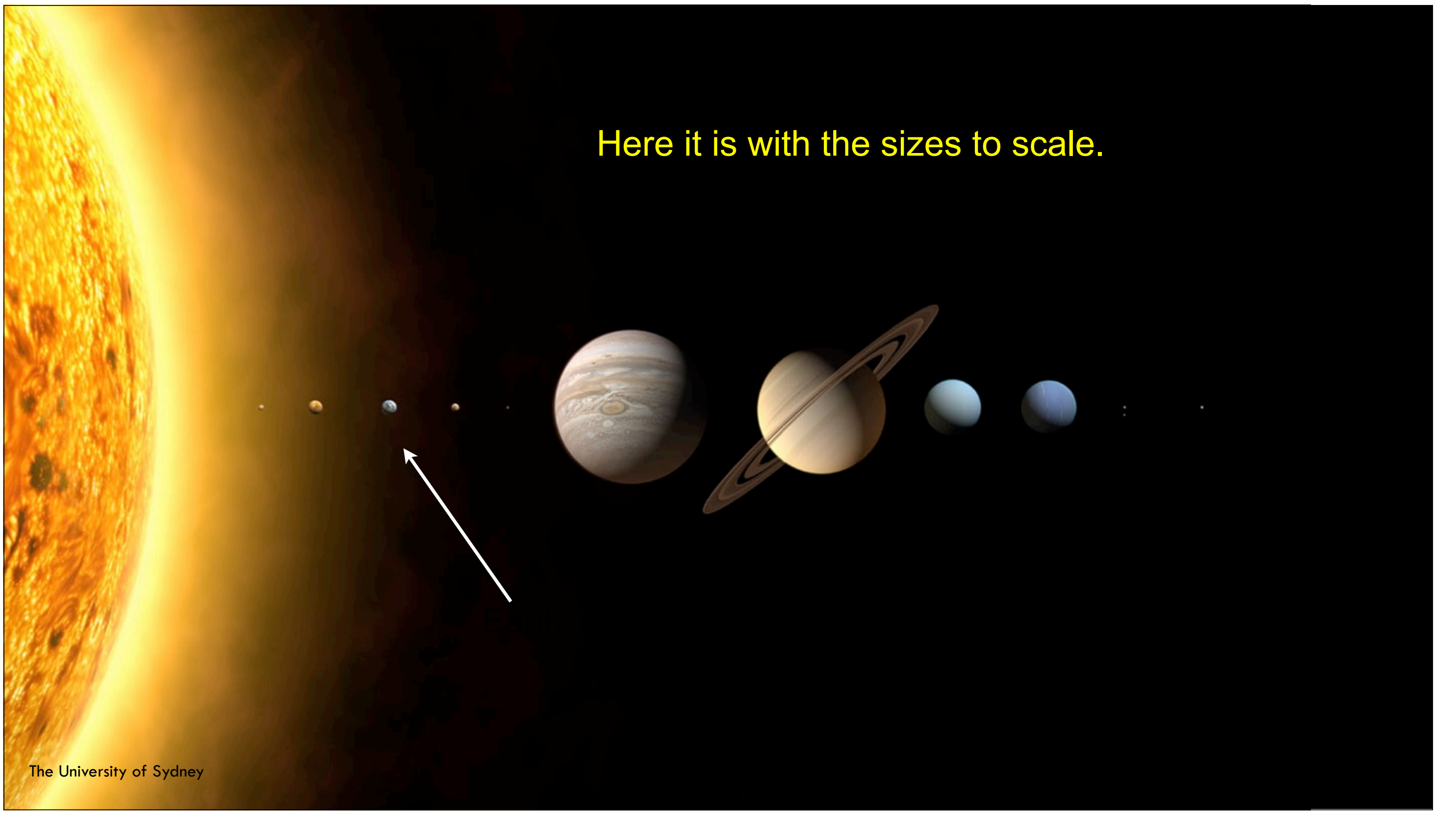
Our Sun is one of billions of other stars, about two-thirds of the way out along an arm in a spiral galaxy, which is one of the biggest galaxies in a small group of galaxies, which is in turn part of a much larger group called the Local Supercluster, which is part of large sheets and bubbles of galaxies in the universe.



"Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the street to the chemist, but that's just peanuts to space."

– Douglas Adams, The Hitchhiker's Guide to the Galaxy (1978)

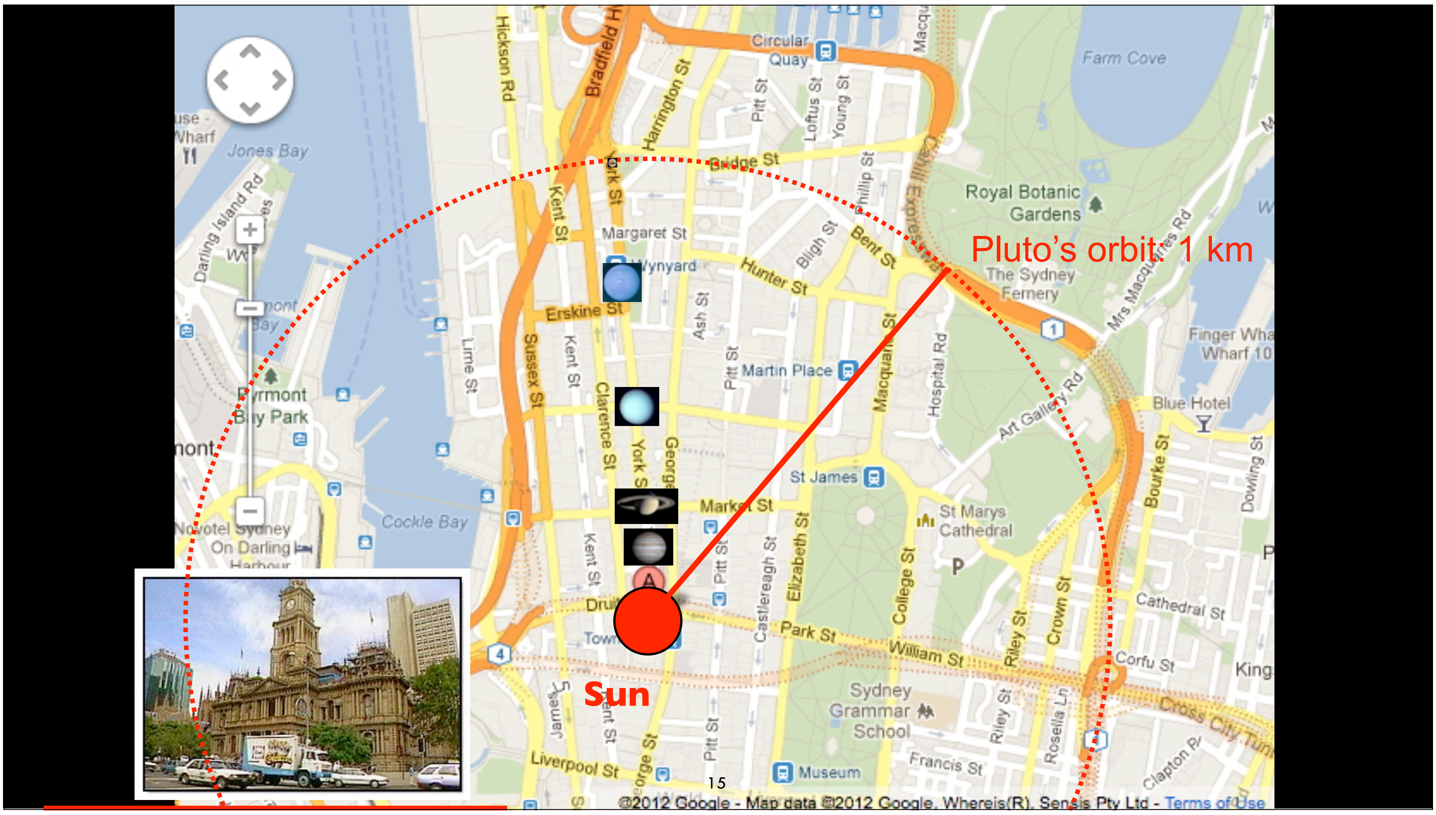

Space is really big. Start with the solar system. This is a view you often see, but it totally misrepresents the relative sizes of the planets.


Here it is with the sizes to scale.
The University of Sydney

This shows the relative sizes of the planets, and how small the Earth is. But this shows us nothing about the scale of the orbits: the solar system.

The best way to visualise the distances is with a scale model.

Object	Size	Distance from Sun
Sun	23 cm (soccer ball)	-
Mercury	0.08 cm (pinhead)	10 m
Venus	0.2 cm (peppercorn)	18 m
Earth	0.2 cm (peppercorn)	25 m
Mars	0.1 cm (pinhead)	38 m
Jupiter	2.4 cm (walnut)	130 m
Saturn	2.0 cm (macadamia)	238 m
Uranus	0.9 cm (peanut)	478 m
Neptune	0.8 cm (peanut)	749 m
Pluto	0.04 cm (pinhead)	983 m


Pluto's orbit: 1 km
Sun
Circular Quay
Bridge St
Margaret St
Wynyard
Erskine St
Hunter St
Martin Place
Market St
St James
Royal Botanic Gardens
The Sydney Fernery
St Marys Cathedral
Sydney Grammar School
Park St
William St
Liverpool St
Museum
Cockle Bay
Pyrmont Bay Park
Jones Bay
Farm Cove
Blue Hotel
Cross City Tunnel
15
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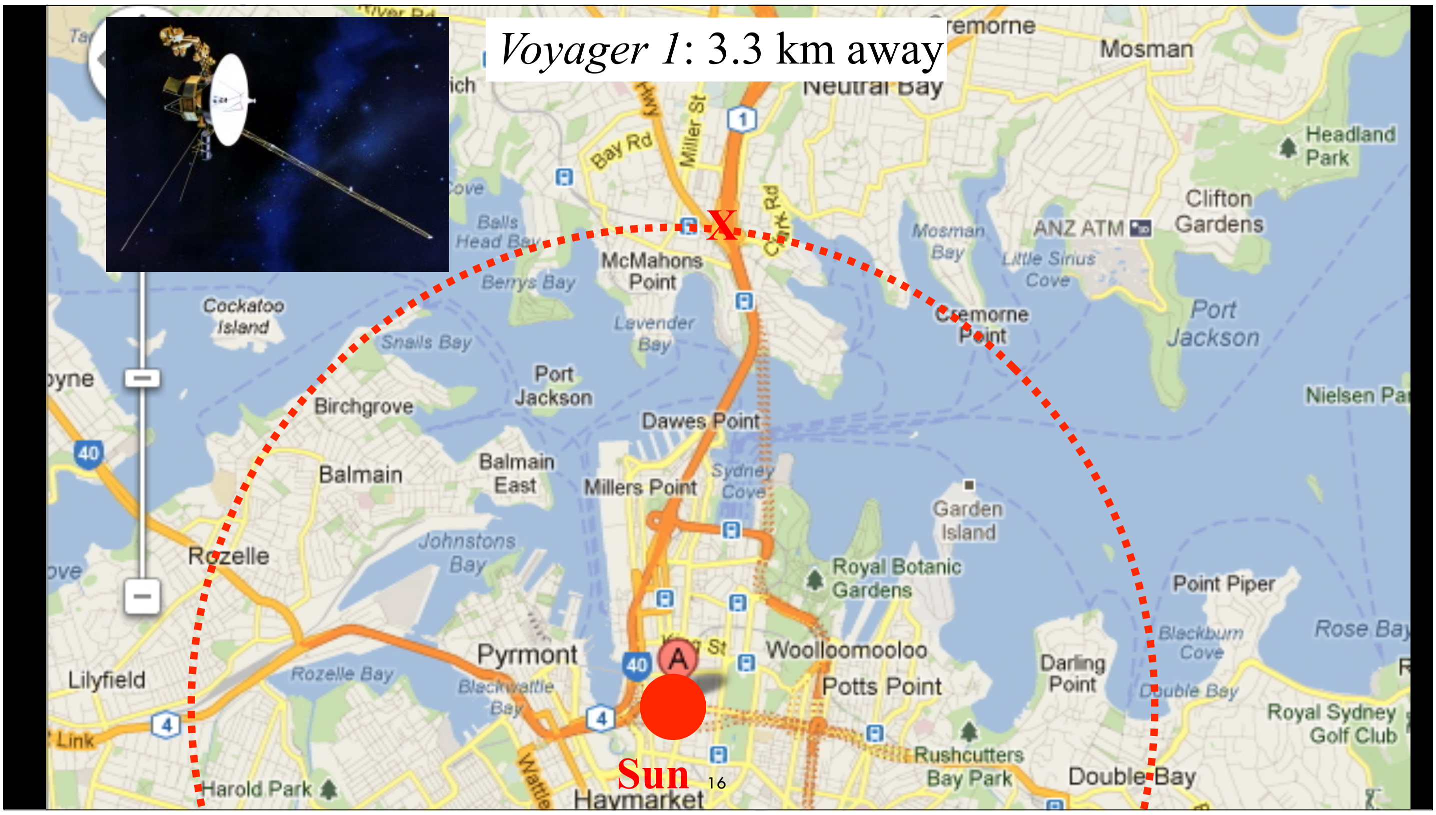
Voyager 1: 3.3 km away
X
Sun
Mosman
Neutral Bay
Headland Park
Clifton Gardens
ANZ ATM
Mosman Bay
Little Sirius Cove
McMahons Point
Berrys Bay
Lavender Bay
Cremorne Point
Port Jackson
Nielsen Park
Cockatoo Island
Snails Bay
Birchgrove
Port Jackson
Dawes Point
Balmain
Balmain East
Millers Point
Sydney Cove
Garden Island
Johnstons Bay
Rozelle
Royal Botanic Gardens
Point Piper
Rose Bay
Blackburn Cove
Lilyfield
Rozelle Bay
Pyrmont
Woolloomooloo
Potts Point
Darling Point
Double Bay
Royal Sydney Golf Club
Rushcutters Bay Park
Double Bay
Harold Park
Haymarket
16


One light year: 1600 km
Sun
Timor Sea
Darwin
Kakadu National Park
Litchfield National Park
Katherine
Gulf of Carpentaria
Cape York Peninsula
Cape Tribulation
Port Douglas
Palm Cove
Kuranda
Cairns
Great Barrier Reef
Kimberley Ranges
Kununurra
NORTHERN TERRITORY
Bungle Bungle National Park
Broome
Tennant Creek
Townsville
Whitsunday Island
Mackay
Port Hedland
Gladstone
Gibson Desert
Uluru National Park
Alice Springs
QUEENSLAND
Fraser Island
Sunshine Coast
Ningaloo Reef
WESTERN AUSTRALIA
Ayers Rock
Monkey Mia
Meekatharra
Simpson Desert
Brisbane
Toowoomba
SOUTH AUSTRALIA
Surfers Paradise
Kalbarri National Park
Nullarbor Plain
Coober Pedy
Bourke
Byron Bay
Gold Coast
Geraldton
Nambung National Park
Broken Hill
Coffs Harbour
Kalgoorlie
NEW SOUTH WALES
Perth
Wave Rock
Blue Mountains National Park
Great Australian Bight
Sydney
A.C.T.
Esperance
Adelaide
Canberra
Margaret River
Albany
Kangaroo Island
VICTORIA
South Pacific Ocean
Mt. Gambier
Indian Ocean
Great Ocean Road
Melbourne
Wilsons Promontory National Park
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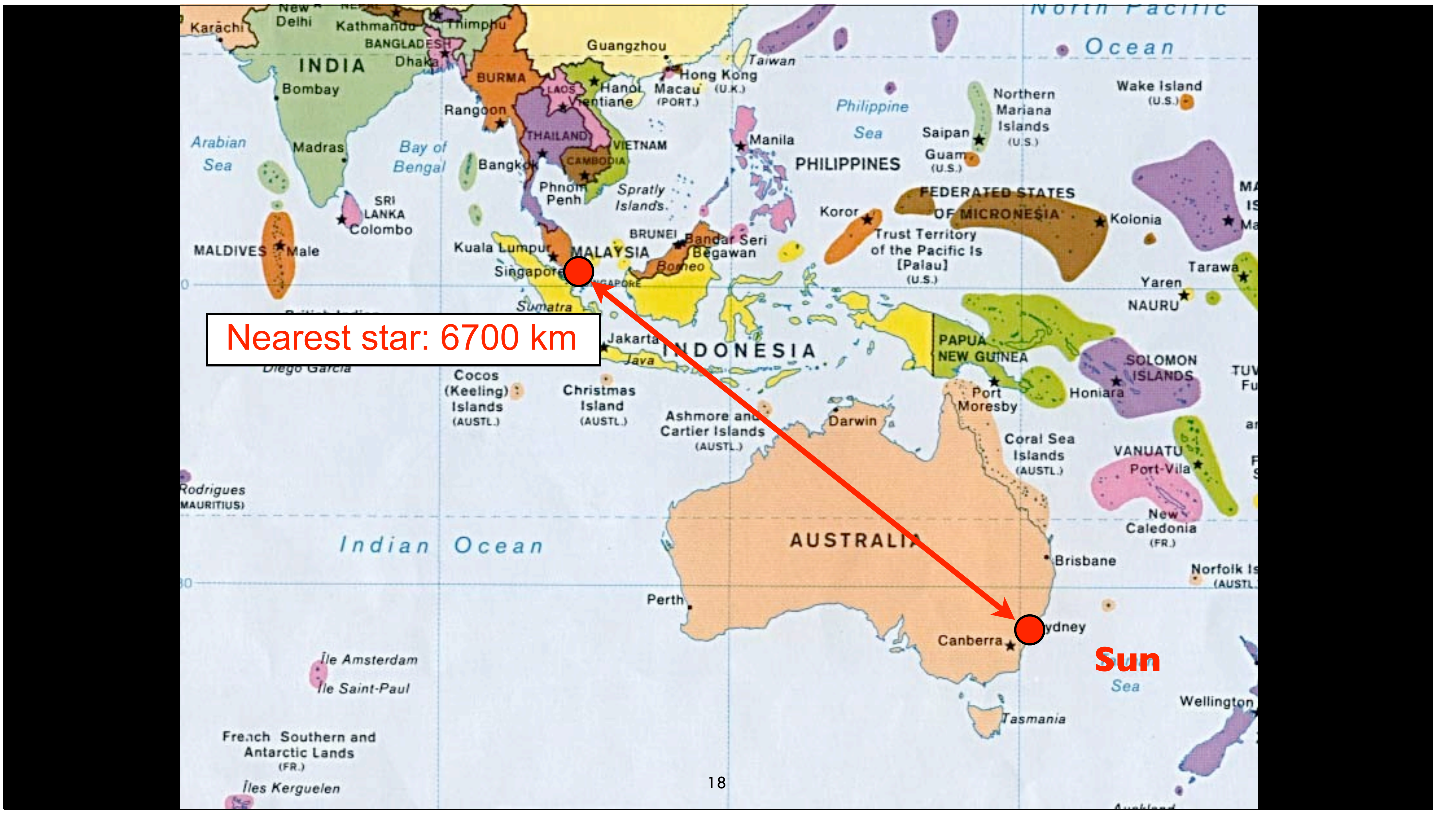

Nearest star: 6700 km
Sun
Karachi
New Delhi
Kathmandu
Thimphu
INDIA
BANGLADESH
Dhaka
Guangzhou
Taiwan
North Pacific Ocean
BURMA
Hanoi
Hong Kong (U.K.)
Bombay
LAOS
Vientiane
Macau (PORT.)
Northern Mariana Islands (U.S.)
Wake Island (U.S.)
Rangoon
Philippine Sea
Arabian Sea
Madras
Bay of Bengal
THAILAND
Bangkok
VIETNAM
Manila
Saipan
CAMBODIA
PHILIPPINES
Guam (U.S.)
Phnom Penh
Spratly Islands
SRI LANKA
Colombo
FEDERATED STATES OF MICRONESIA
Koror
Kolonia
BRUNEI
MALDIVES
Male
Kuala Lumpur
MALAYSIA
Bandar Seri Begawan
Trust Territory of the Pacific Is [Palau] (U.S.)
Singapore
Borneo
Tarawa
Yaren
NAURU
Sumatra
Jakarta
INDONESIA
PAPUA NEW GUINEA
Java
SOLOMON ISLANDS
Diego Garcia
Cocos (Keeling) Islands (AUSTL.)
Christmas Island (AUSTL.)
Port Moresby
Honiara
Ashmore and Cartier Islands (AUSTL.)
Darwin
Coral Sea Islands (AUSTL.)
VANUATU
Port-Vila
Rodrigues (MAURITIUS)
New Caledonia (FR.)
Indian Ocean
AUSTRALIA
Brisbane
Norfolk Is (AUSTL.)
Perth
Sydney
Canberra
Île Amsterdam
Île Saint-Paul
Sea
Wellington
Tasmania
French Southern and Antarctic Lands (FR.)
Îles Kerguelen
18

On this scale, the nearest star, Alpha Centauri, is at a distance of 6,700 km = the distance to Singapore.

There is not a *single object* approaching the size of a soccer ball between here and Singapore.

Remember this scale: we'll refer to it again.

"The chief characteristic of the universe is, I would say, emptiness. There is infinitely more nothing in the universe than anything else."

– John Updike, *The Poorhouse Fair*

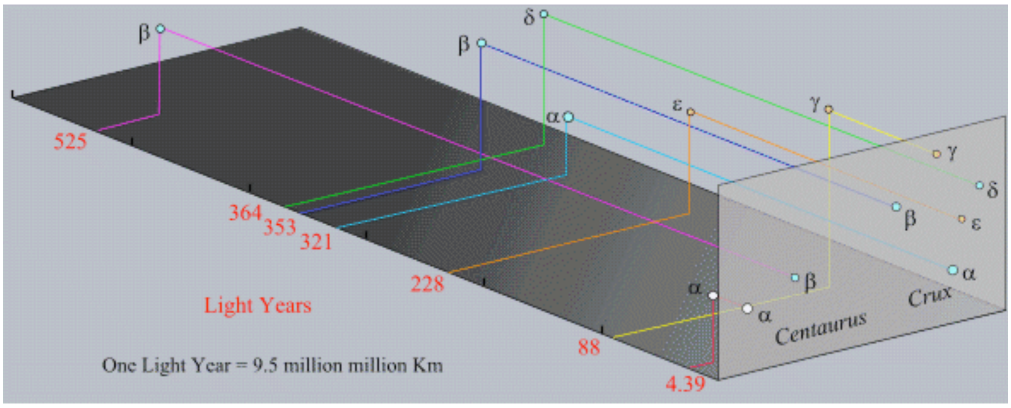
Because of these ridiculous distances, astronomers have defined some special units to make the numbers more manageable:

- An *astronomical unit* (AU) is the average Earth-Sun distance: 1 AU = 149.6 million km
- A *light year* (ly) is the distance light travels in a year: 1 ly = 9,461,000,000,000 km = 63,000 AU
- A *parsec* (pc) is about 3.26 ly; we'll find out where this comes from in a few lectures

The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.

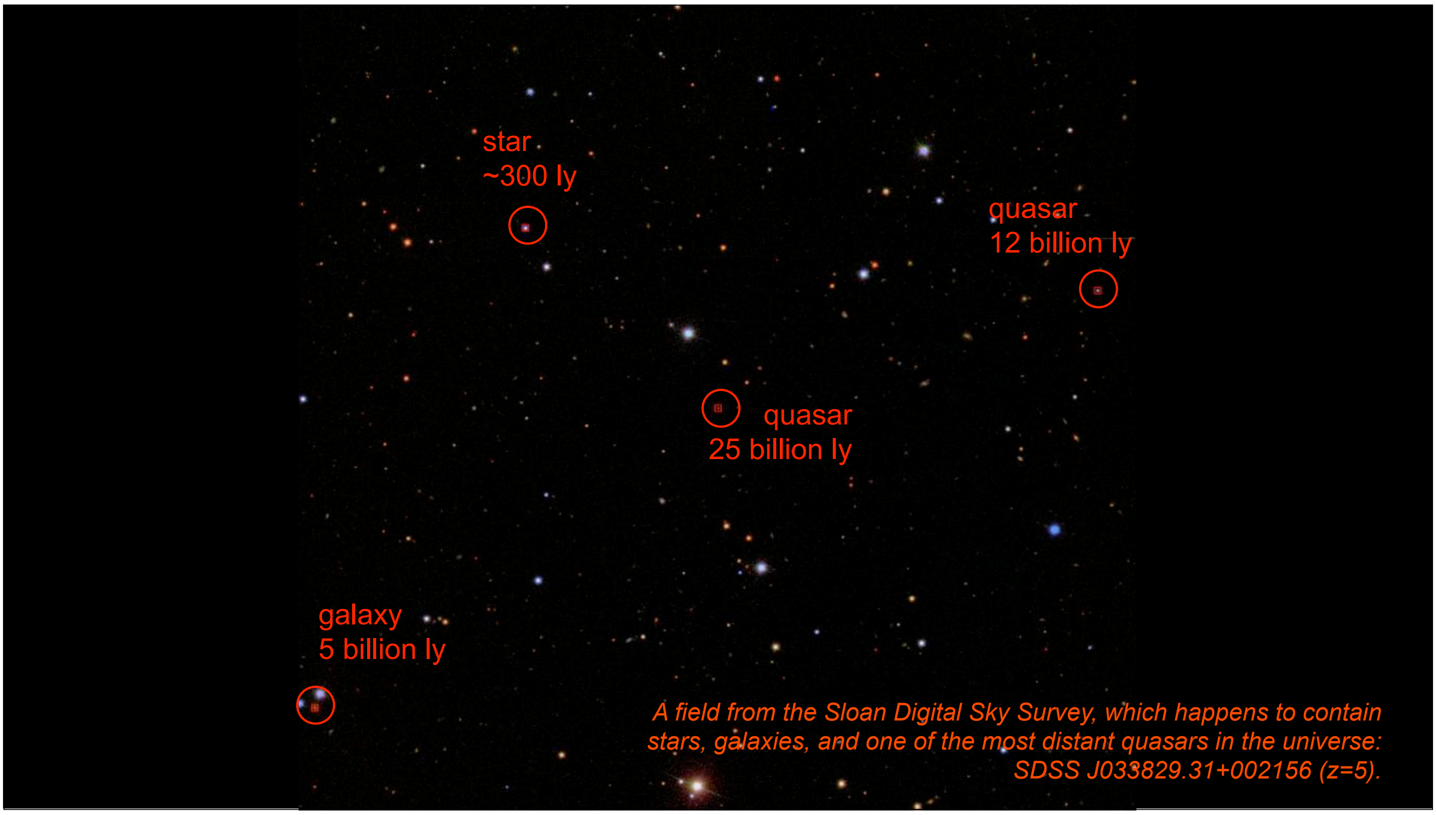
Object	**Distance**	**Lookback time**
Moon	384,400 km	1.3 s
Sun	150,000,000 km	8 m
Pluto	39.5 AU	5.5 h
Nearest star	40 trillion km = 4.3 ly	4.3 y
LMC	168,000 ly	168,000 y
Andromeda galaxy	2,000,000 ly	2,000,000 y
Nearest quasar 3C273	2.4 billion ly; z=0.158	2.4 billion y
Most distant object	z=8.6	13.1 billion y

One problem we have is that when we look at the sky, we have no notion how far away objects are.



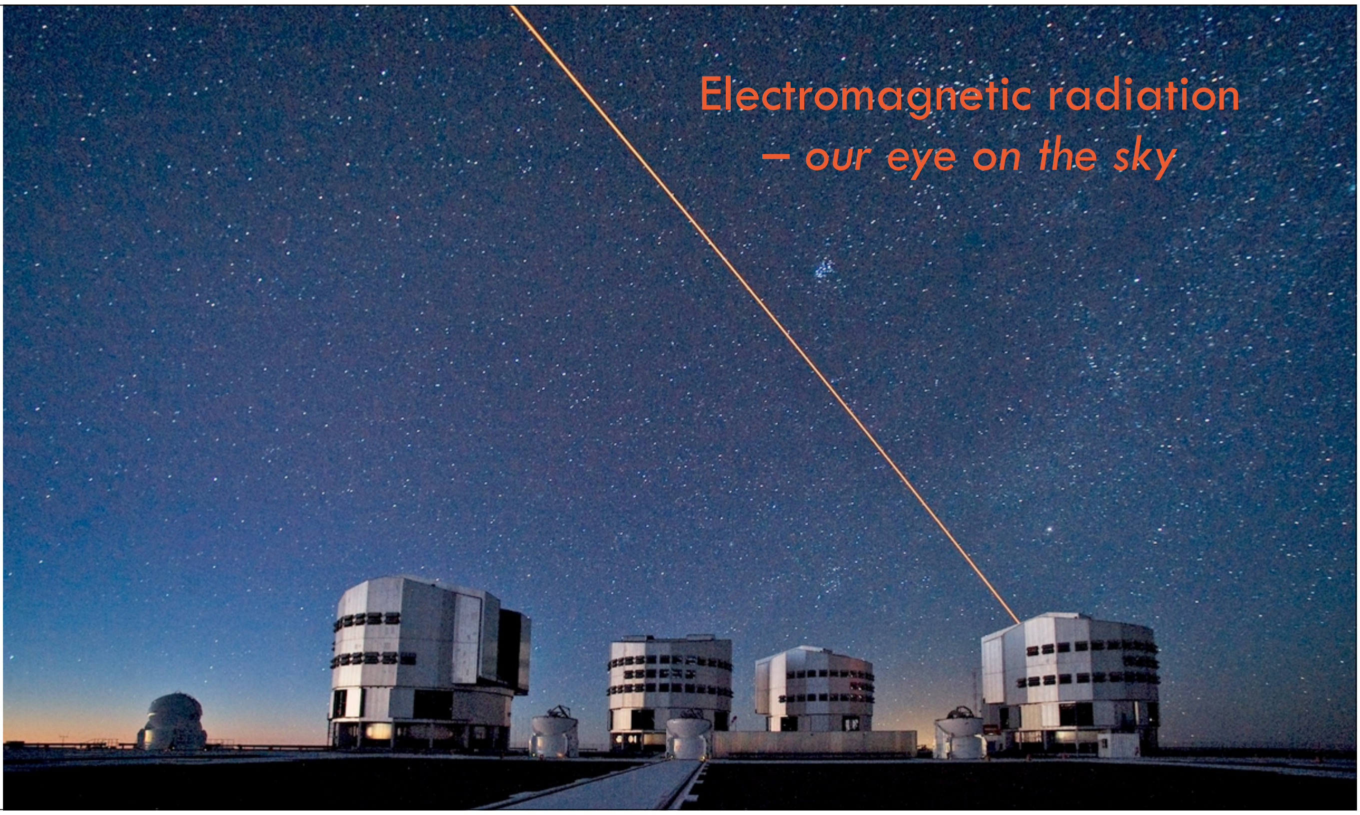
The stars of the Southern Cross and the Pointers have similar brightnesses, but very different distances.

The coloured object is the asteroid Ceres (distance ~3 AU) passing near the galaxy group NGC 3607 (distance 60 million light years)



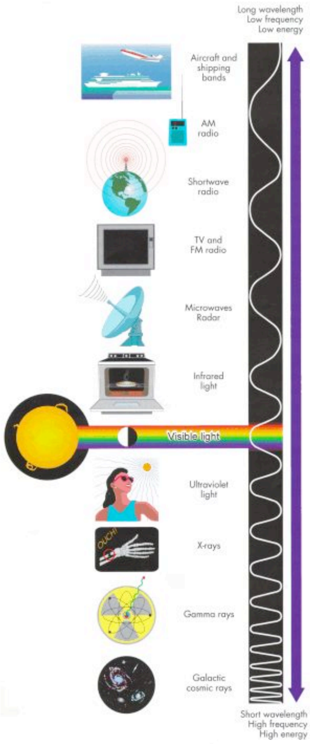
A field from the Sloan Digital Sky Survey, which happens to contain stars, galaxies, and one of the most distant quasars in the universe: SDSS J033829.31+002156 (z=5).

We will be discussing how we find the distances to astronomical objects later in the course.



Astronomy is not an experimental science: astronomers can't get their hands on their subject matter. Everything we know about the cosmos, we know by *remote sensing*.

Visible light is the most obvious means by which we can observe the universe. But there are many other sorts of radiation we can't see with our eyes: these include radio waves, infrared, ultraviolet, X-rays and gamma rays. Together, all these forms of radiation make up the *electromagnetic spectrum* – the complete spectrum of radiation.



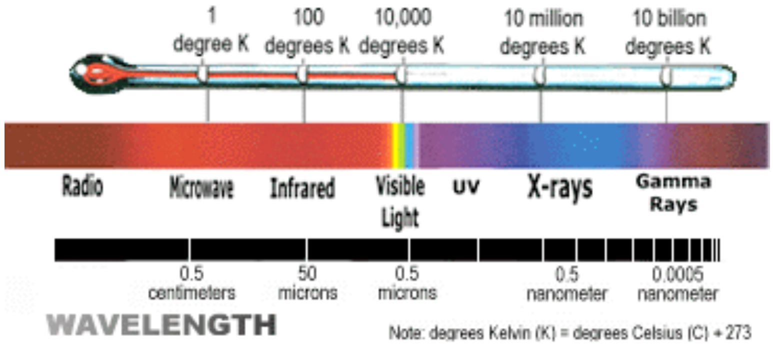
Wavelength	*Frequency*
10 km (shipping)	30 kHz
1 km (aircraft)	300 kHz
300 m (AM)	1000 kHz = 1 MHz
50 m (shortwave)	6 MHz
3m (FM radio)	100 MHz
50 cm (TV)	600 MHz
1 cm (microwave)	
10 micron	
0.5 micron = 500 nm	
100 nm	
1 nm	
0.001 nm = 1pm	

Visible light makes up only a tiny fraction of the electromagnetic spectrum. Our eyes can see less than an octave of the spectrum, from wavelengths of 400 nm to 700 nm. Astronomical observations cover more than *65 octaves* of the spectrum, from low-frequency radio waves to ultra-high-energy gamma rays.

From now on, when we use the word "light", we mean "electromagnetic radiation", not just visible light.

All electromagnetic radiation travels at the *speed of light*, which is usually written as c = 300,000 km/s.

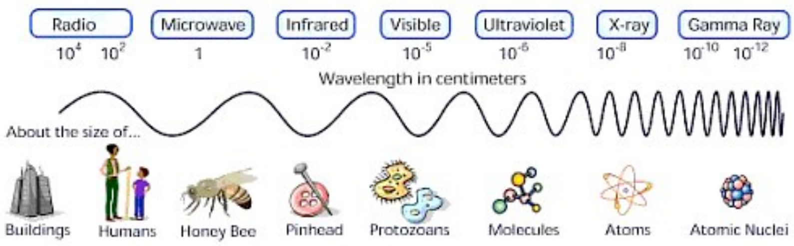
The wavelength at which an object radiates most depends principally on its *temperature*.



Cool objects radiate most at long wavelengths,
hot objects at short wavelengths.

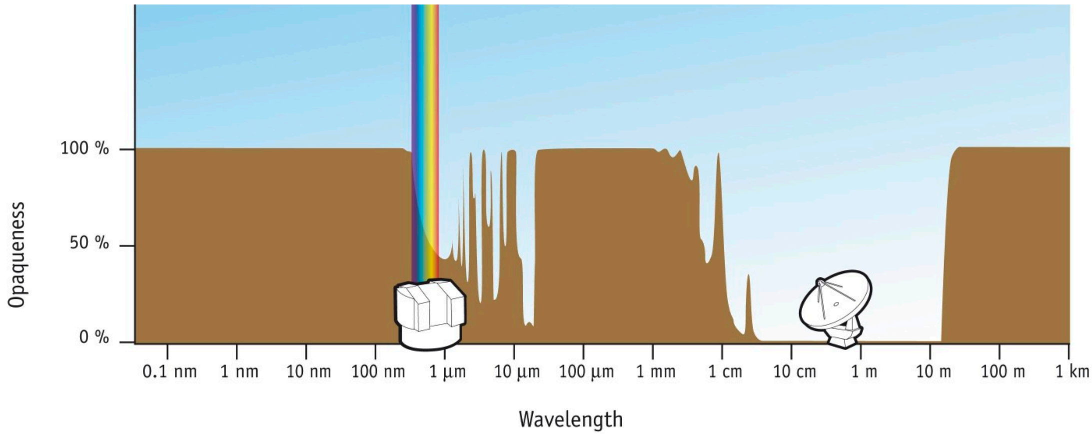
The Sun radiates most at the wavelength of visible light.

All forms of EM radiation are the same, but they *seem* very different because of the very different scales involved.



Radiation can pass around objects which are much smaller than the wavelength.

The Earth's atmosphere is opaque to nearly all parts of the EM spectrum.

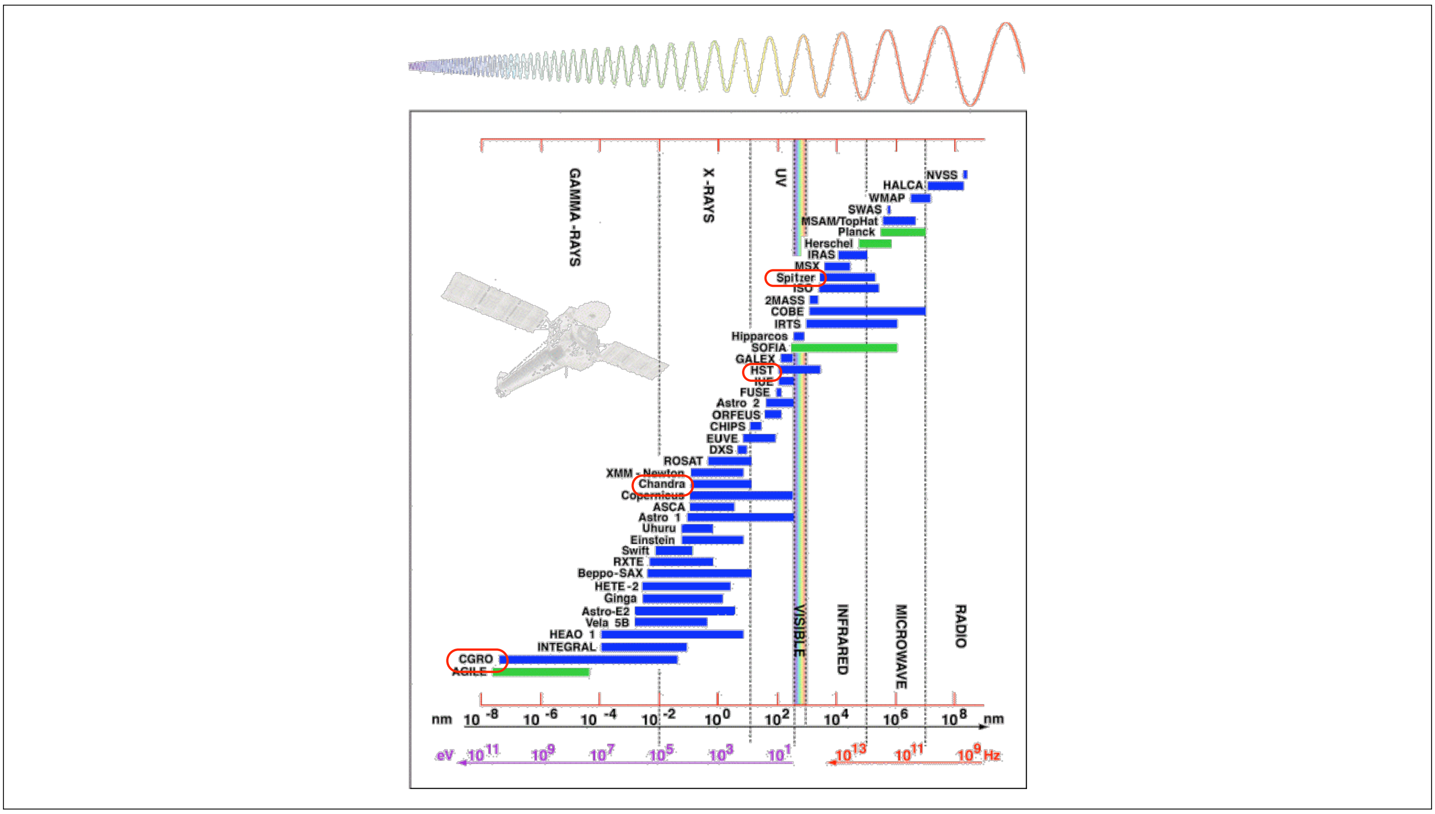


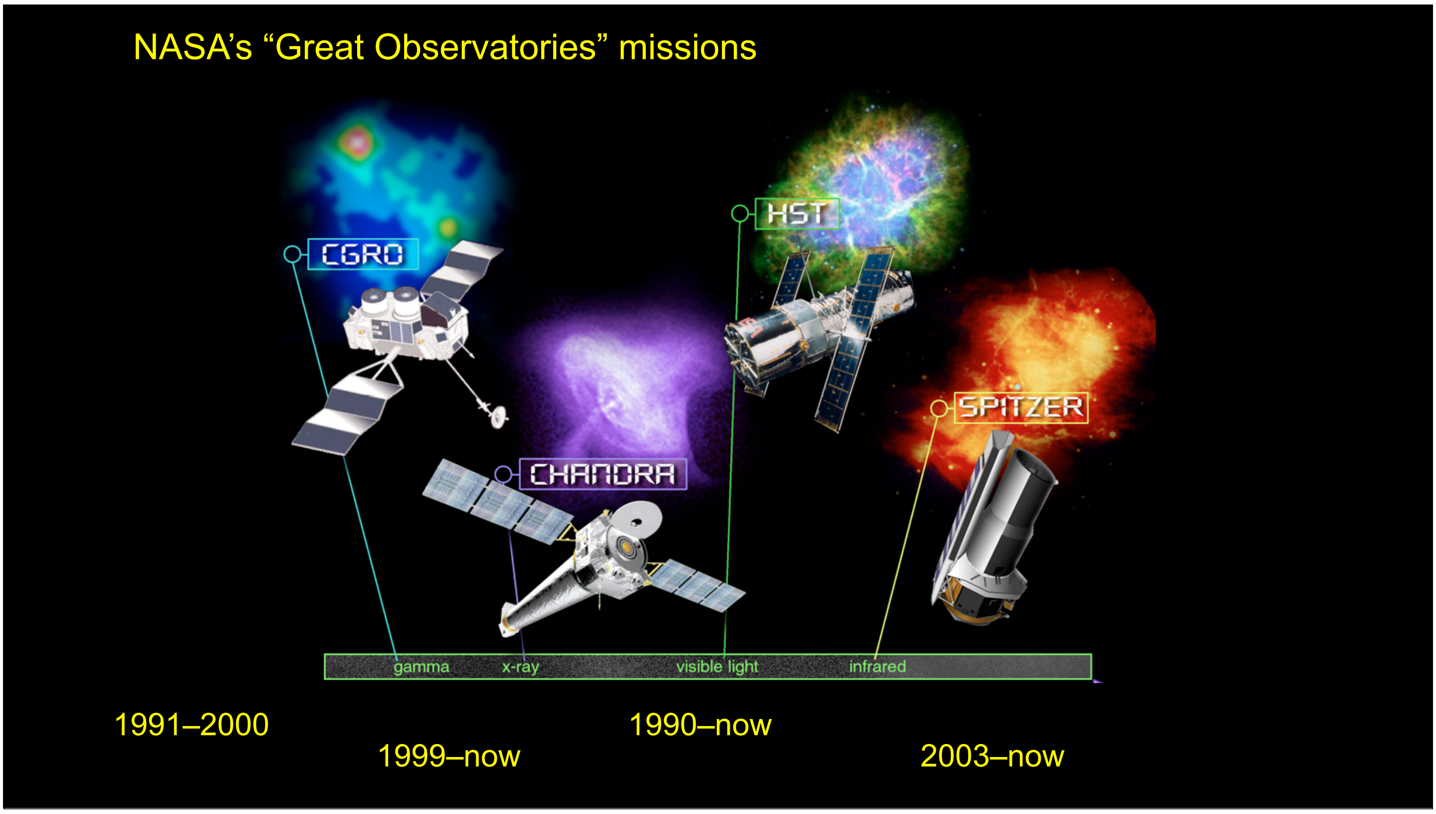
Only visible and radio waves can reach the surface.

So we need to go outside the Earth's atmosphere in order to see many parts of the electromagnetic spectrum. And even for regions which we can see from Earth, like visible light, going into space has advantages, like removing the twinkle the atmosphere produces.

Here are the most important past and present astronomical satellites*

** plus a couple of ground-based missions*


GAMMA-RAYS
X-RAYS
UV
VISIBLE
INFRARED
MICROWAVE
RADIO
NVSS
HALCA
WMAP
SWAS
MSAM/TopHat
Planck
Herschel
IRAS
MSX
Spitzer
ISO
2MASS
COBE
IRTS
Hipparcos
SOFIA
GALEX
HST
IUE
FUSE
Astro 2
ORFEUS
CHIPS
EUVE
DXS
ROSAT
XMM - Newton
Chandra
Copernicus
ASCA
Astro 1
Uhuru
Einstein
Swift
RXTE
Beppo-SAX
HETE-2
Ginga
Astro-E2
Vela 5B
HEAO 1
INTEGRAL
CGRO
AGILE
nm 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} nm
eV 10^{11} 10^{9} 10^{7} 10^{5} 10^{3} 10^{1} 10^{13} 10^{11} 10^{9} Hz


NASA's "Great Observatories" missions
CGRO
HST
CHANDRA
SPITZER
gamma
x-ray
visible light
infrared
1991–2000
1999–now
1990–now
2003–now

Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The optical image shows a bright elliptical galaxy obscured by a dark dust lane.

Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

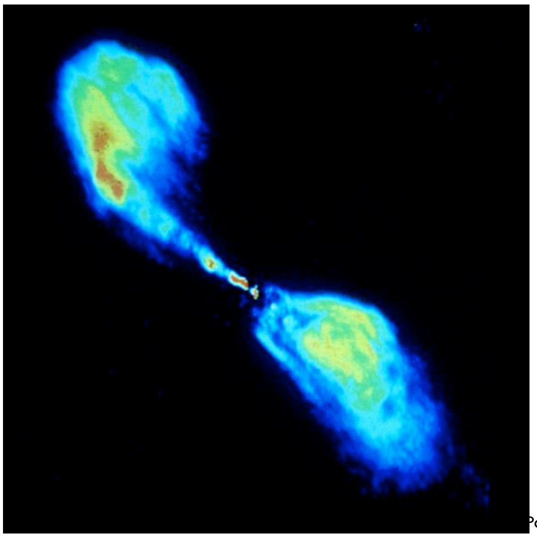
In the ultraviolet image the galaxy has almost disappeared: all we see is the dark dust lane shrouding the bright centre.

Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The infrared image shows that the dust lane is actually the remains of a spiral galaxy.

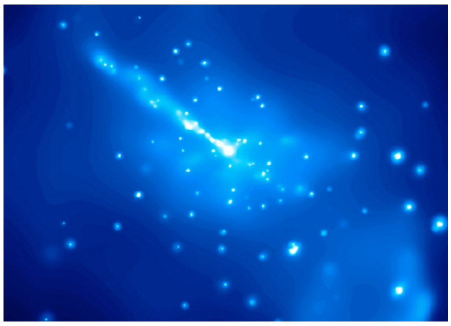
Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The radio image is a surprise! We see a totally new structure, looking like jets shooting out of the centre and spreading out.



Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The X-ray image also shows a jet, this time only pointing in one direction. We believe it is emanating from a supermassive black hole at the centre of the galaxy.



Here are all those images together.

X-ray ultraviolet optical infrared radio

short wavelength — long wavelength

Composite X-ray (blue), radio (pink and green), and optical (orange and yellow) image of the galaxy Centaurus A

Why do these images look so different?

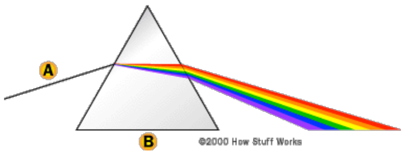
Since objects of different temperatures emit light of different wavelengths, then observing at different wavelengths allows us to "see" objects of different temperatures, which means very different conditions.

Type of radiation	Characteristic temperature	Typical objects emitting this radiation
Gamma-ray	$> 10^8$ K	Neutron stars, accretion disks around black holes
X-ray	10^6–10^8 K	Shocked gas; neutron stars; supernova remnants
Ultraviolet	10^4–10^6 K	Supernova remnants; very hot stars; quasars
Optical	1000–10,000 K	Stars; galaxies; emission nebulae; reflection nebulae
Infrared	10–1000 K	Cool stars; interstellar gas; planets
Radio	< 10 K	Cosmic background; cold interstellar gas; supernova remnants

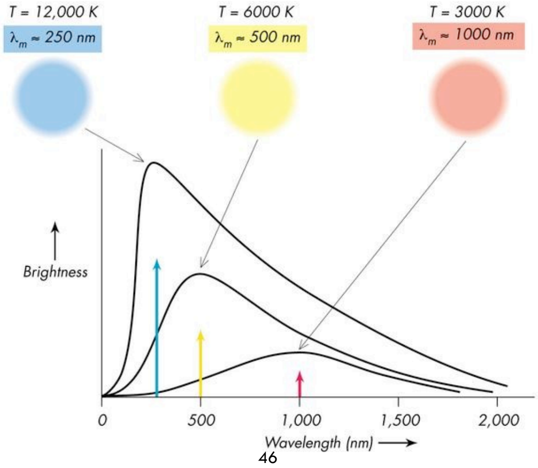
Spectra: separating light

Almost every source of EM radiation produces photons of many wavelengths at once.

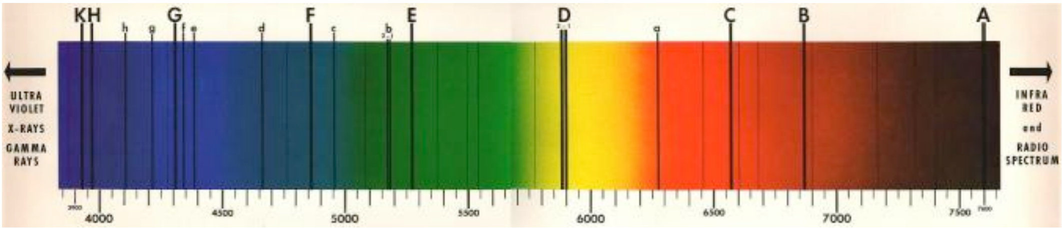
A *spectrometer* is a device for sending light of different wavelengths in different directions.



Many objects when heated show the same shape to their spectrum, called a *blackbody spectrum*. A black body gives off radiation at many wavelengths, but has a strong peak at a particular wavelength. The hotter the object, the shorter the wavelength: *hotter* objects have *bluer* spectra.



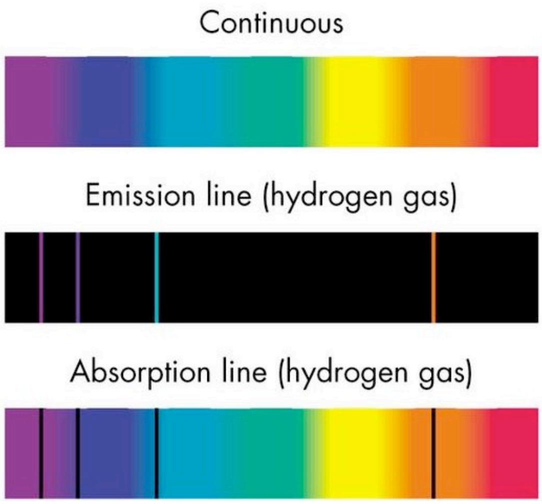
Joseph Fraunhofer, in 1814, discovered that the solar spectrum was not just a continuous band of colour, but was crossed by numerous dark bands, which never changed their position.

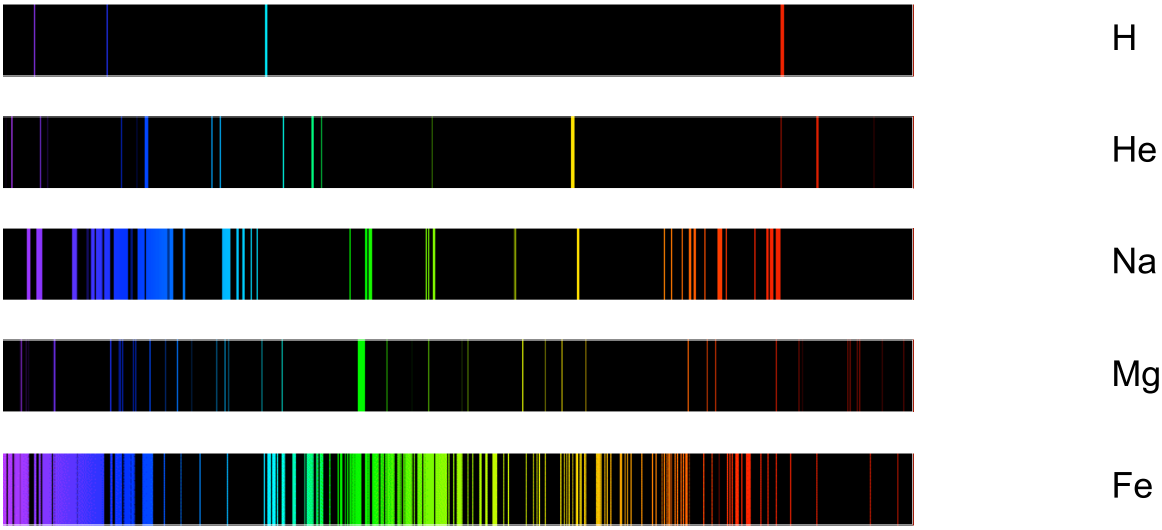


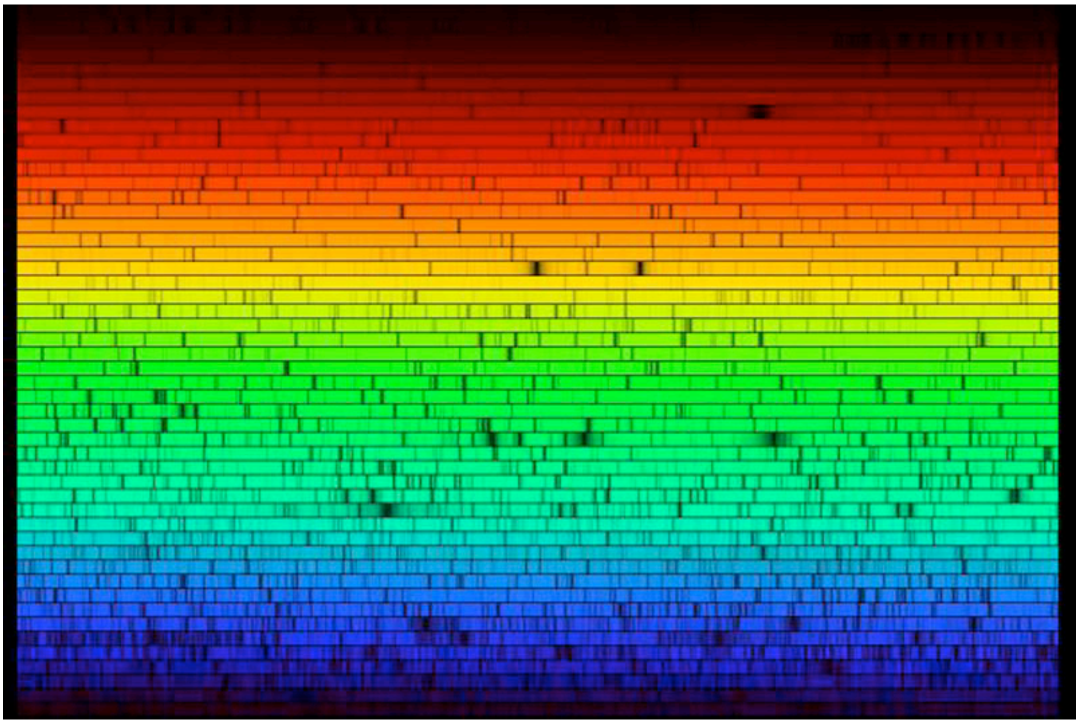
Gustav Kirchhoff, in 1859, discovered that a heated substance produced a series of coloured lines, and that this pattern was unique for each chemical element.

He found that there are three different types of spectra:

- *Continuous* spectrum (hot, high pressure gas or solid)
- Bright *emission* lines (hot, low pressure gas)
- Dark *absorption* lines (cool, low pressure gas)





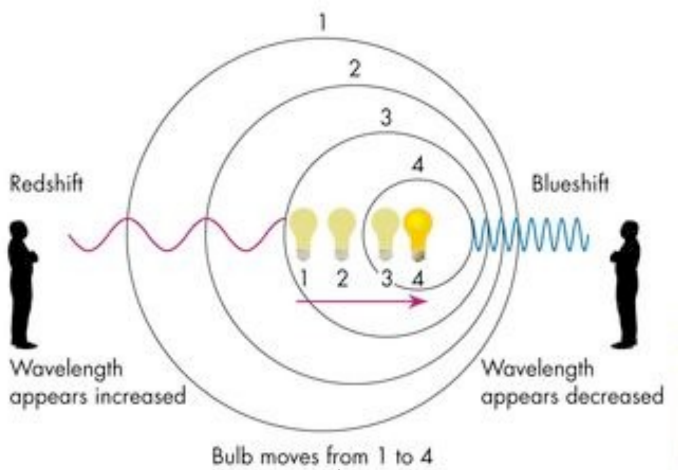


High resolution solar spectrum

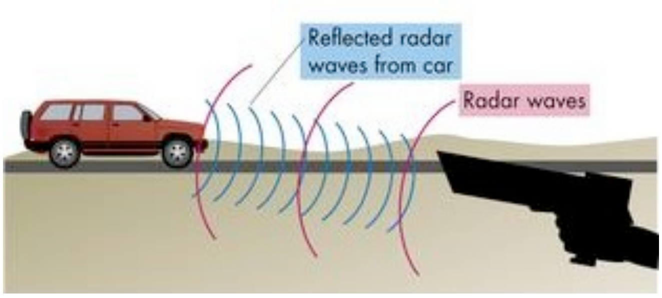
Each element produces a unique fingerprint.

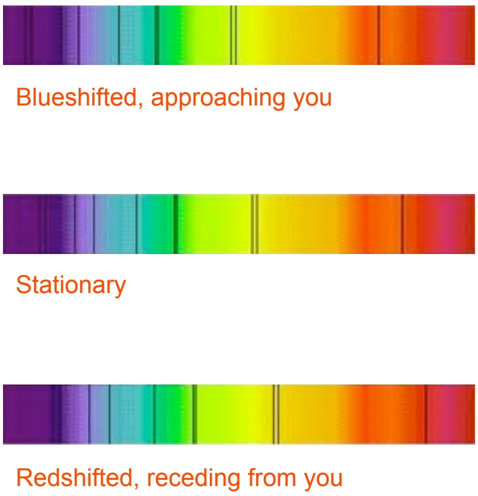
In many ways, this represents the beginning of astronomy as a science. Suddenly it was possible to study the composition of heavenly bodies using nothing but light!

Because light is made of waves, the wavelength will change if the emitting object is moving: the *Doppler effect*. A source moving towards you has a shorter wavelength (*blueshift*), a source moving away has a longer wavelength (*redshift*).



This is how police speed radars work: the shift in frequency gives the speed of the car.





The amount of shift you get depends on the velocity: faster objects have the spectral lines shifted further from the rest wavelength.

So astronomers have to use a lot of inference to understand what is going on:

- images: *the shape of an object*
- spectra: *what it's made of, how fast it's moving...*
- multi-wavelength images: *how it works*

Case study: Hanny's Voorwerp

In 2007, Hanny van Arkel, a Dutch school teacher and volunteer for the Galaxy Zoo project, discovered a giant green object near an ordinary spiral galaxy.

Nothing like it had ever been seen before.

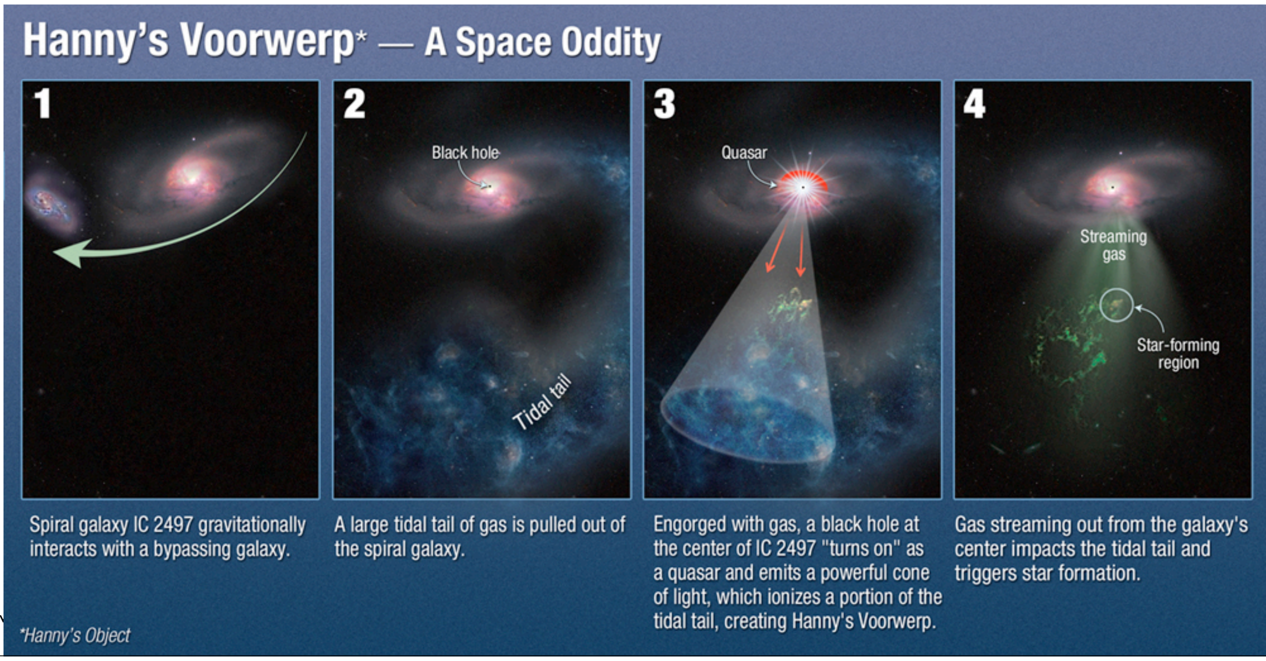
Original SDSS image of Hanny's

Astronomers all over the world used many telescopes at different wavelengths to try to understand it.

Spectra of the object showed that it is at the same distance as the nearby galaxy, and is about the same size. The light is produced by hot glowing gas: the green colour is produced by ionised oxygen atoms.

Hubble image of Hanny's Voorwerp

Our best guess is that the gas, ripped from another galaxy, is glowing because it was illuminated by a quasar which has since switched off.



Further reading

For the whole course:

- For astronomical images, you can't do better than the "**Astronomy Picture of the Day**" website, http://antwrp.gsfc.nasa.gov/apod/astropix.html. Not only does this have a fabulous archive of the most amazing pictures (and a new one every day), each image also has links to many other interesting sites where you can follow up the topic. I've used APOD as the source for many of the images here, mostly because it's so convenient. If you prefer to have your pictures in a form you can hold (and show off to friends), a selection has been published as a book, in "**Universe: 365 Days**" by R. J. Nemiroff and J. T. Bonnell (Harry N. Abrams, 2003), with a follow-up volume called "**Astronomy: 365 Days**" (2006)

- There are many excellent introductory-level texts which cover the material in this course. A good example is "**Horizons: Exploring the Universe**" by Michael A. Seeds (Brooks/Cole, 2000); or the text we use for our first-year introductory astronomy course is "**The Cosmic Perspective**" by Bennett et al. (Pearson, 2010)

- NASA has a site called "**Imagine the Universe**", http://imagine.gsfc.nasa.gov/index.html which is a good place to start for finding out about all things astronomical. It also has excellent links to other places on the Web to find information.

For tonight's lecture:

- **"Imagine the Universe"** has a nice page about the electromagnetic spectrum: http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html

- For more galaxies and other objects in many wavelengths, take a look at IPAC's **"The Multiwavelength Astronomy Gallery"**, http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/ ; or the **"Multiwavelength Milky Way"**, http://mwmw.gsfc.nasa.gov/

- Mike Brown, the discoverer of Eris, has an excellent blog about scale in the Solar System, and how hard it is to depict planetary scales accurately, at http://www.mikebrownsplanets.com/2009/08/planetary-placemats.html

- There's a lovely book on the same topic: **"Sizing up the Universe:** The cosmos in perspective" by J. Richard Gott and Robert J. Vanderbei (National Geographic, 2011). It's like a meditation about size and scale, and the centrepiece is their "Logarithmic Map of the Universe" – a version of which can be found at http://www.astro.princeton.edu/universe/ (though not as pretty). xkcd has a similar idea in the cartoon just called "Height" http://xkcd.com/482/

- The Galaxy Zoo project is a "citizen science" project where members of the public assist in research by classifying galaxies observed in the Sloan Digital Sky Survey: http://www.galaxyzoo.org/. There are other associated projects: classifying features on the Moon (https://www.zooniverse.org/project/moonzoo), finding planets around other stars (https://www.zooniverse.org/project/planethunters), and classifying Hubble galaxy pictures (https://www.zooniverse.org/project/hubble)

- Hanny van Arkel has her own blog, where she talks about the discovery of her *voorwerp*: http://www.hannysvoorwerp.com/

Sources for images used:

- Title image: The barred spiral galaxy NGC 613, taken by ESO's Very Large Telescope. From ESO Press Release, 19 December 2003 http://www.eso.org/public/outreach/press-rel/pr-2003/phot-33-03.html
- Eta Aquarid & Milky Way Reflections: image by Mike Taylor, from APOD 2014 May 9 http://apod.nasa.gov/apod/ap140509.html
- Earth: View of the Earth from space, Eastern hemisphere, from "The Blue Marble: True-color global imagery at 1 km resolution" http://earthobservatory.nasa.gov/Newsroom/BlueMarble
- Valles Marineris hemisphere of Mars: from NASA Planetary Photojournal,http://photojournal.jpl.nasa.gov/catalog/PIA00407
- *Cassini* view of Jupiter: from NASA Planetary Photojournal, http://photojournal.jpl.nasa.gov/catalog/PIA02873
- Asteroid Ida and its moon Dactyl: from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/cap/ast/idamnclr.htm
- Callisto (second largest moon of Jupiter): from NASA Planetary Photojournal, http://photojournal.jpl.nasa.gov/catalog/PIA03456
- Hyperion (moon of Saturn): from APOD 2013 Jun 30 http://apod.nasa.gov/apod/ap130630.html
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- Comet: Comet Hale-Bopp in 1997, from APOD 2000 December 27 http://antwrp.gsfc.nasa.gov/apod/ap001227.html
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- Cat's Eye Nebula: APOD 2014 Oct 12 http://apod.nasa.gov/apod/ap141012.html
- Artist's interpretation of the white dwarf star H1504+65: from "Naked White Dwarf Shows its Dead Stellar Engine" http://www.space.com/scienceastronomy/mystery_monday_040705.html
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- Spiral galaxy: M51, from the Hubble Heritage Project, http://heritage.stsci.edu/2005/12a/index.html
- Group of galaxies: the Hickson Compact Group HCG 87; APOD 1999 September 6 http://antwrp.gsfc.nasa.gov/apod/ap990906.html
- Virgo cluster: APOD 2015 Aug 4 http://apod.nasa.gov/apod/ap150804.html
- Hercules cluster: APOD 2014 June 25 http://apod.nasa.gov/apod/ap140625.html
- Sheets and bubbles of galaxies: from the Illustris Project http://www.illustris-project.org/explorer/
- Distance ladder: from Spitzer mission pages http://www.nasa.gov/mission_pages/spitzer/multimedia/pia15818_prt.htm
- Nine planets: Solar system montage, PIA01341 from the NASA Planetary Photojournal http://photojournal.jpl.nasa.gov/catalog/PIA01341
- Planets and sun to scale: from IAU Draft Definition of "planet" http://www.iau.org/public_press/news/detail/iau0601/
- Scale model of the Solar System: from "The Thousand-Yard Model" by Guy Ottewell http://www.noao.edu/education/peppercorn/pcmain.html

- Updike: quoted in Hirshfeld, "Parallax: The Race to Measure the Cosmos", p. 68
- Quasar image: from "High Redshift Quasars in the ING Wide Field Survey", http://www.ing.iac.es/PR/newsletter/news4/science1.html
- Distances of stars in the Southern Cross: from "Distances" by Peter Caldwell, http://users.netconnect.com.au/~astronet/dist.html. Used with permission
- Electromagnetic spectrum: from "Imagine the Universe" http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html
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- Blackbody spectrum: from "Explorations" by Thomas T. Arny, Fig. 3.6 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0306.html
- Fraunhofer lines: from "Quantum Physics" by S. Raychaudruri, http://home.iitk.ac.in/~sreerup/BSO203.html
- Types of spectra: from "Explorations" by Thomas T. Arny, Fig. 3.15 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0315.html
- Doppler shifts: from "Explorations" by Thomas T. Arny, Fig. 3.18 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0318.html
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