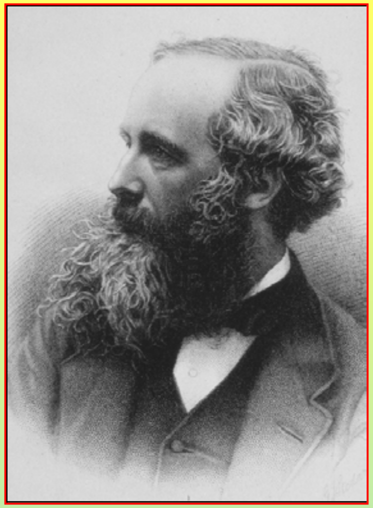
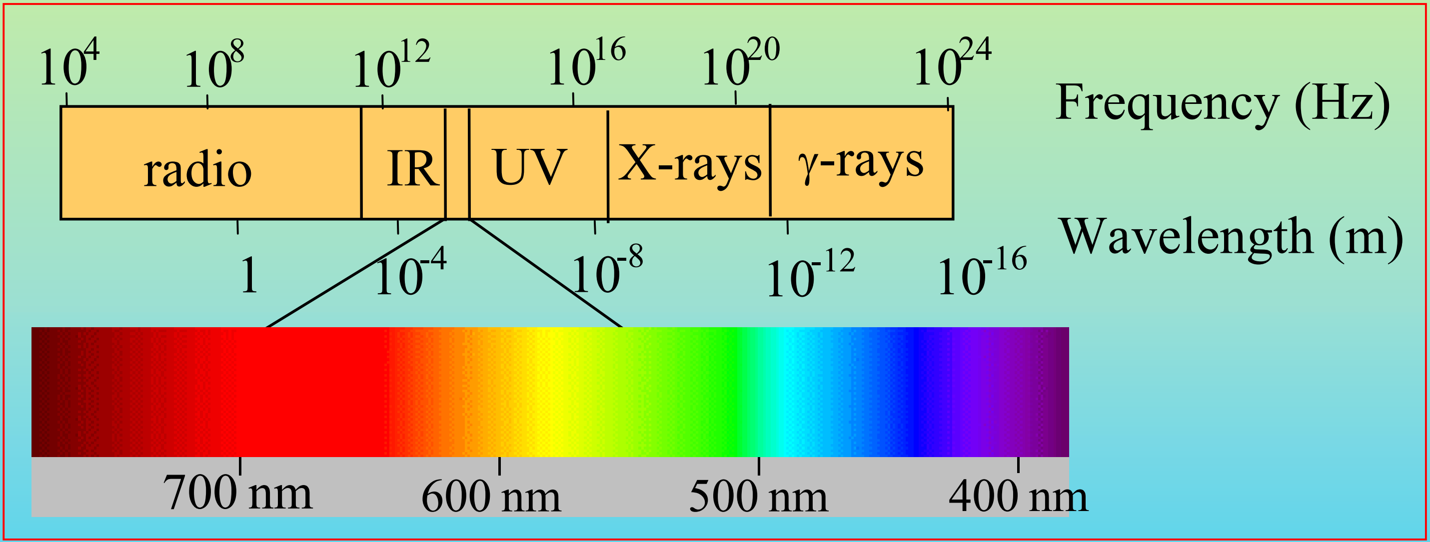
Spectra & Light Sources

- In this section we'll cover
  - the EM spectrum
  - radiation laws
  - continuous spectra
  - discrete spectra
  - the quantum theory of atoms
- Making light
  - evolution of artificial light sources
  - the working of lasers

The Electromagnetic Spectrum


James Clerk Maxwell

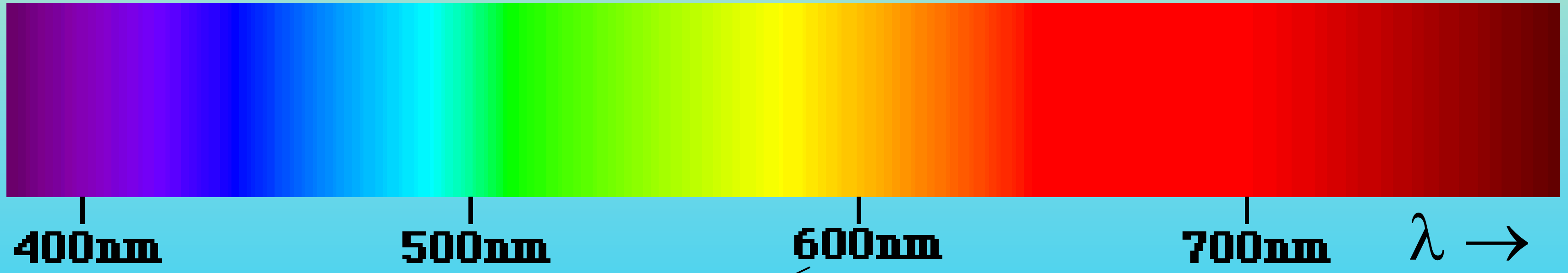
- Light is a tiny part of a huge spectrum of electromagnetic waves



- Light in vacuum has **wavelengths** between ~400 nm and ~800 nm; 1 nm ≡ 10^{-9} m (a nanometer)
- 1 μm ≡ 10^{-6} m (a micron); 1 Å ≡ 10^{-10} m ≡ 0.1 nm

Colour and Wavelength

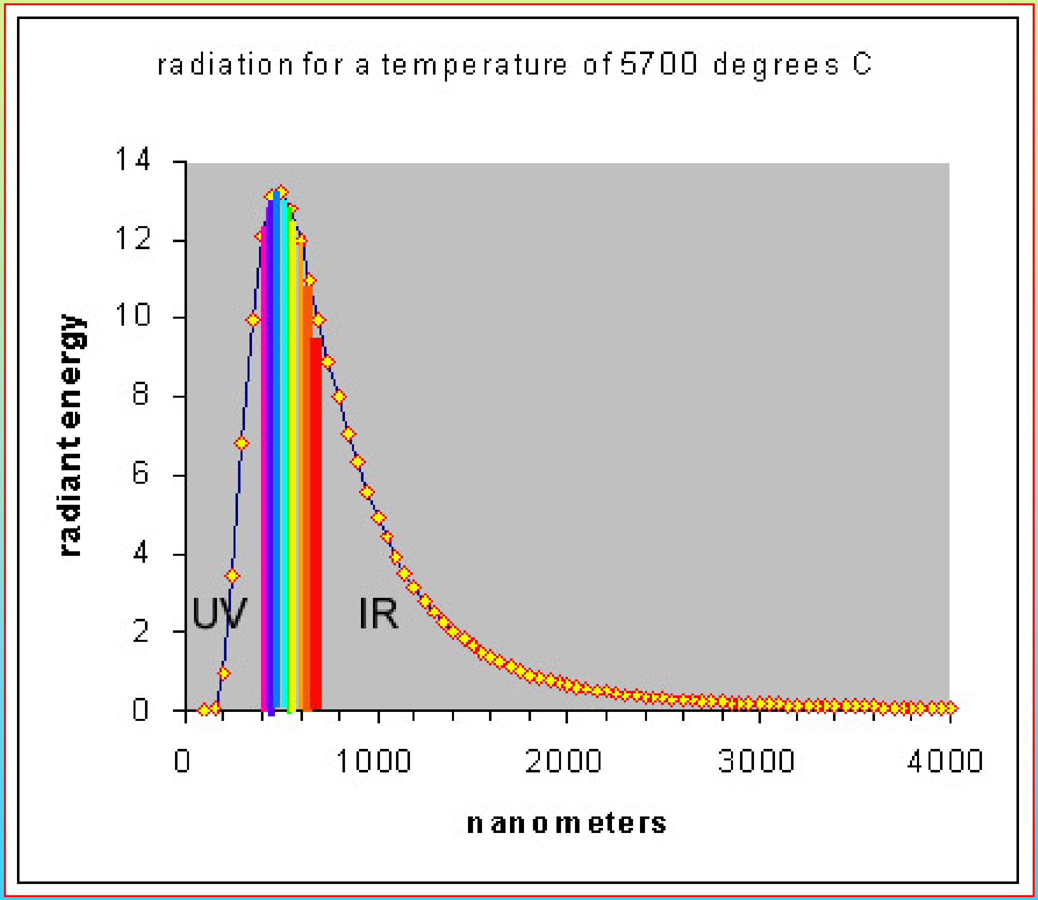
- Colour is related to *frequency*, f, which stays the same as light passes from one medium to another
- In spite of this, spectra are usually labelled by the wavelength, λ, in vacuum of the light



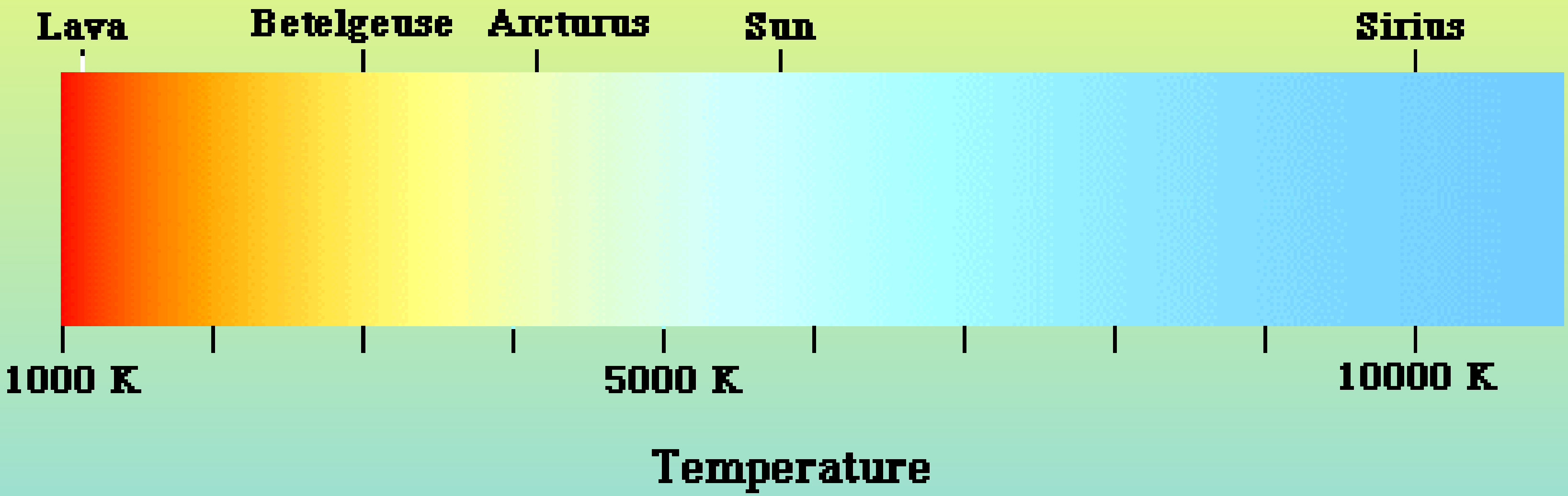
$$\lambda = \frac{c}{f}$$

Hot body emission

- **All bodies** emit electromagnetic radiation
- The spectral spread of this radiation is determined by the **temperature** of the body and a fundamental law of physics, Planck's radiation law



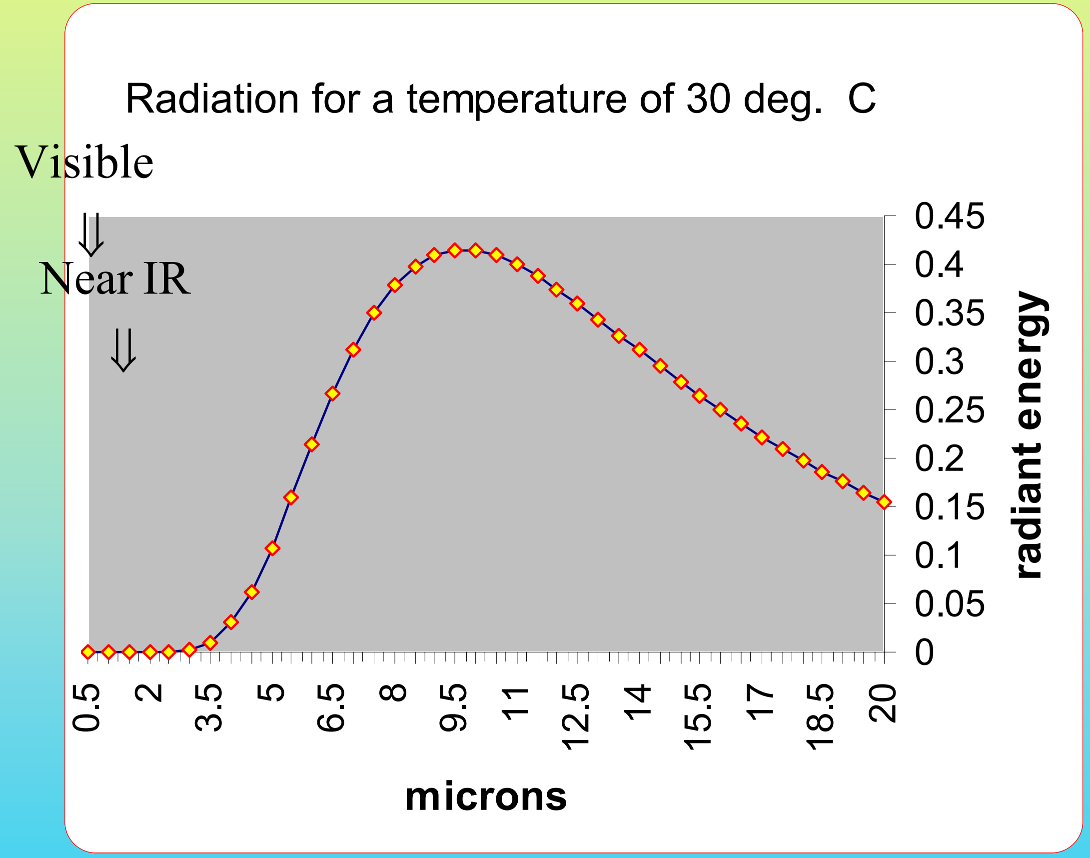
Appearance of hot bodies



- Red is the colour of bodies that just glow; yellow, white and blue for really hot bodies
  - the concept of **colour temperature** is used by architects and others to label the spectrum of incident light they perceive

Emission from cooler bodies

- The spectrum of radiant energy was predicted by Planck
- Bodies at room temperature emit radiation in the far IR



- Man-made devices can detect at other wavelengths than visible light

Planck's Radiation Law

- Planck deduced that a perfect radiator at temperature T (in K) would emit an energy density E_λ at wavelength λ of:

Planck, the elder statesman of German science

$$E_\lambda = \frac{8\pi hc}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]$$

h - Planck's constant

c - speed of light in vacuum

k - Boltzmann's constant

- This is known as **Planck's Radiation Law**
  - his great innovation was *h* – Planck's constant, 6.626×10^{-34} J s

Wavelength of Maximum Radiation (λ_{max})

- Hot bodies emit the maximum amount of radiation at a wavelength that is inversely proportional to their absolute temperature
- *Wien's Law*:

$$\lambda_{max} = \frac{3000}{T}, \lambda \text{ in } \mu m, T \text{ in } K$$

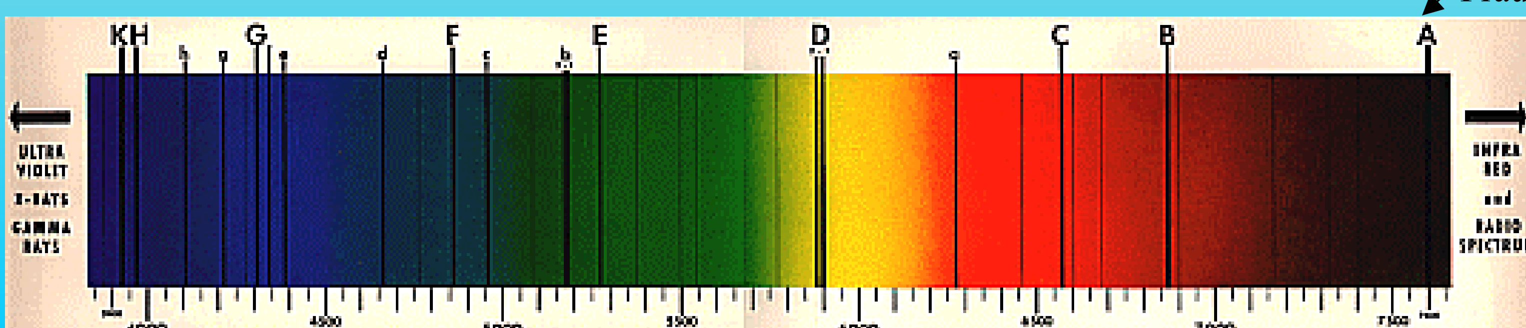
Wilhelm Wien
1864 - 1928 Germany

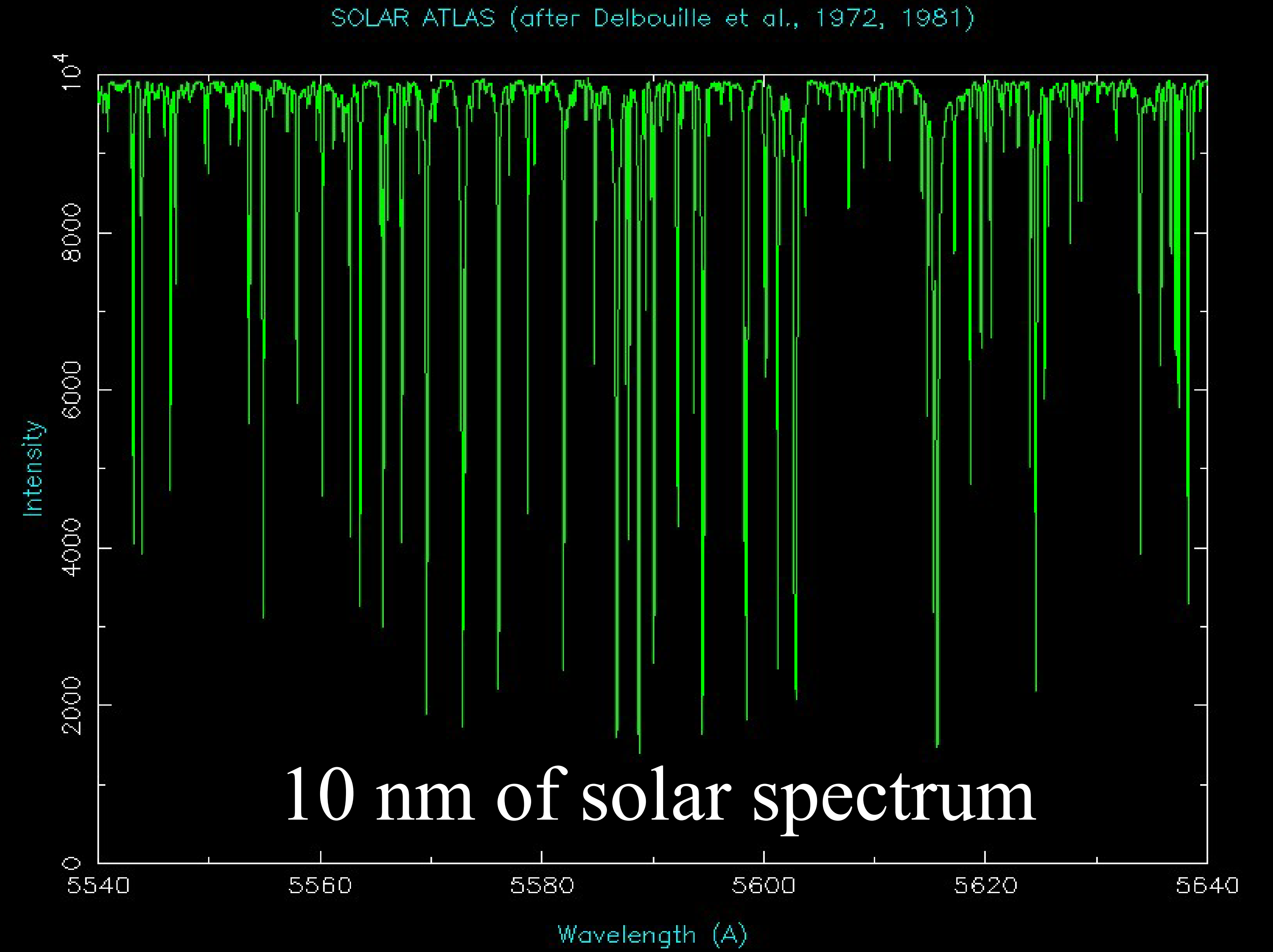
- e.g. Sun at 6000 K, $\lambda_{max} = 0.5\ \mu m$ (*green*)
- e.g. us at 300 K, $\lambda_{max} = 10\ \mu m$ (*far infrared*)

The Sun’s spectrum

- The Sun’s spectrum looks continuous, like a black body, through a low dispersion prism
- Closer examination shows it is covered with dark lines
  - these were first examined in detail ~1814 by Joseph Fraunhofer, who gave the conspicuous ones letters
  - each dark line is produced by one element

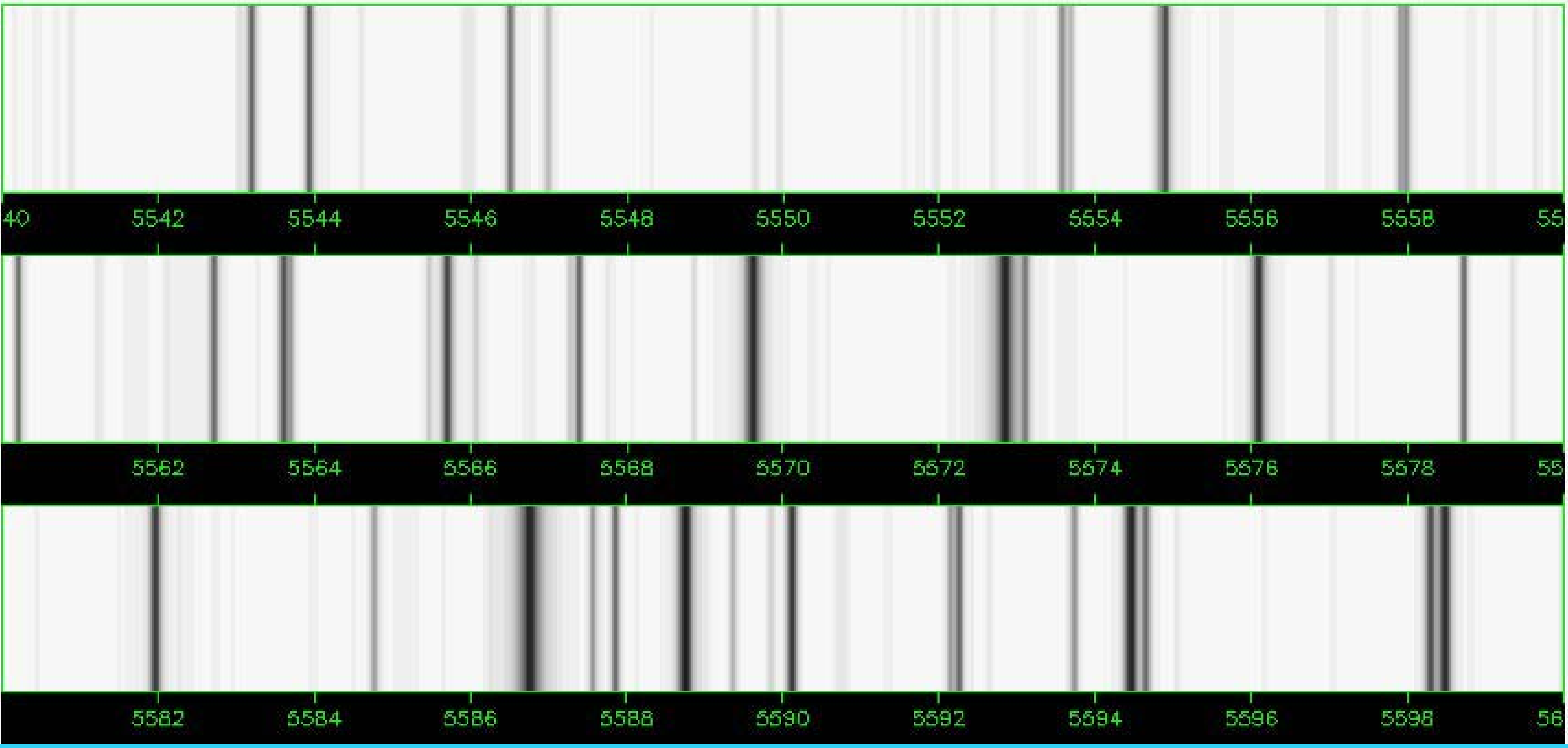
Fraunhofer letters





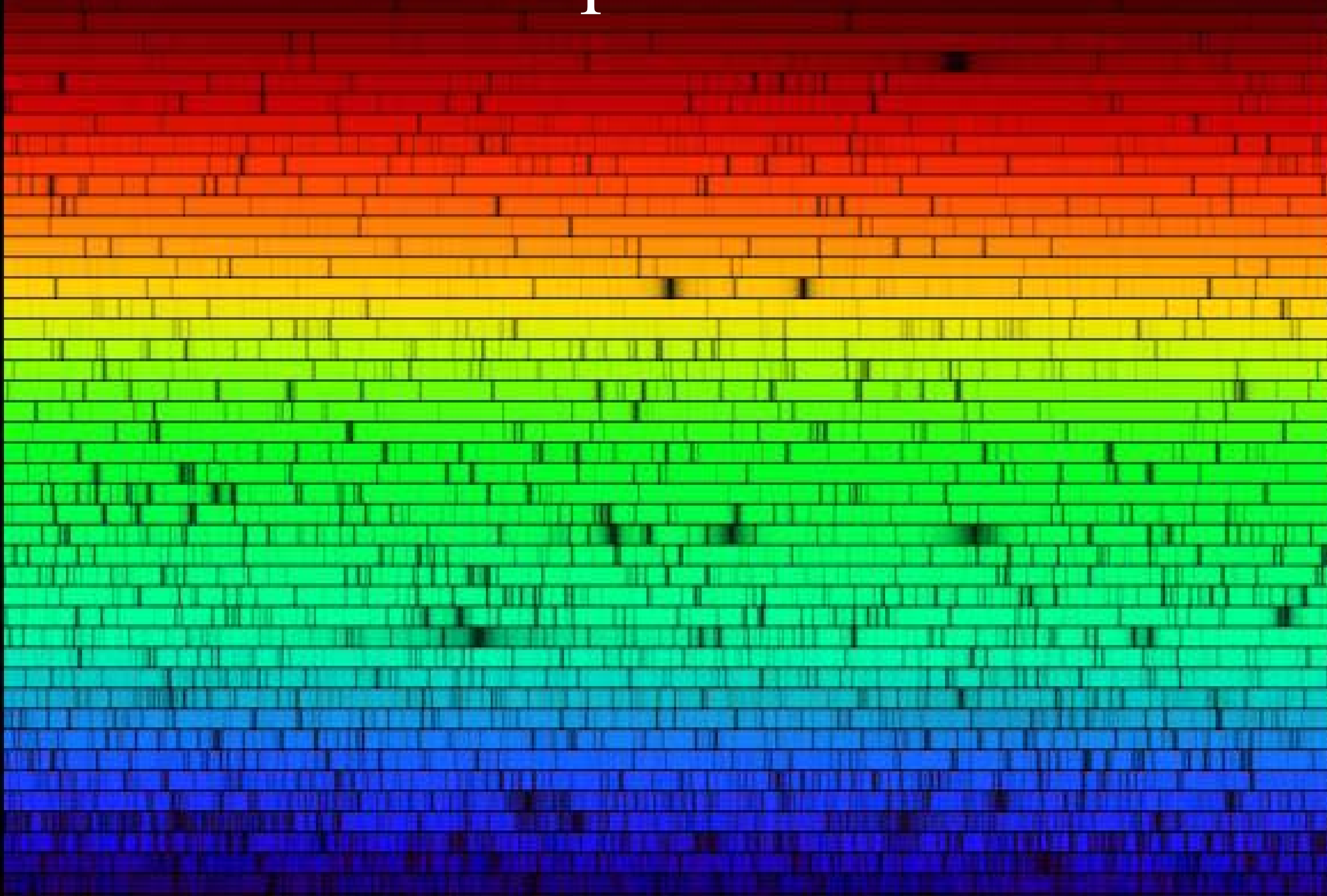
10 nm of solar spectrum

Photographic Appearance of same part of Sun's spectrum



- Wavelengths here are in Å (≡ 0.1 nm)

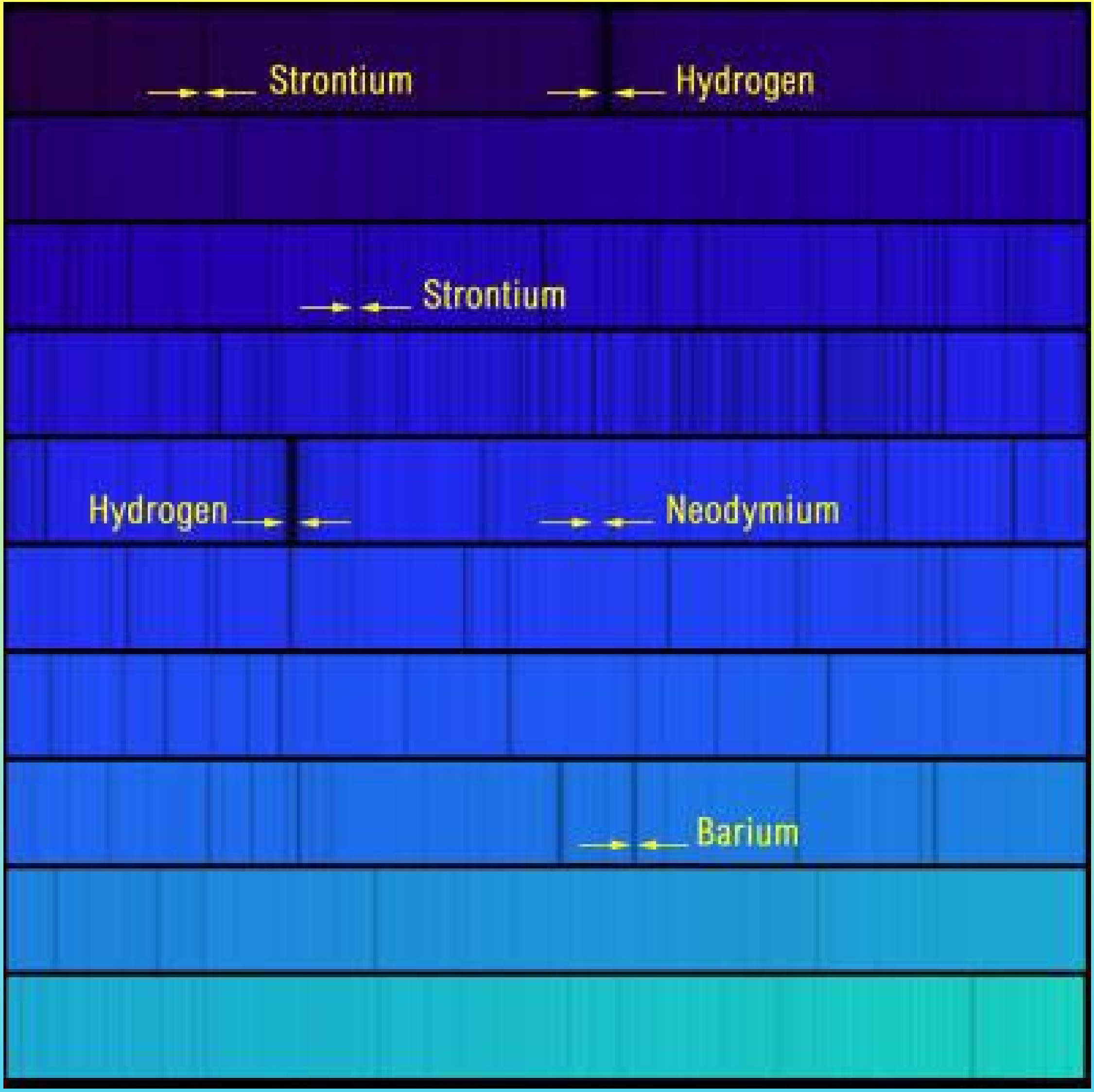
Visible Solar Spectrum in 45 Slices



Courtesy Nigel Sharp NOAO/NSO/Kitt Peak. FTS/AURA/NSF

Spectral line Identification

- Each element produces many spectral lines
- The spectral lines have well defined frequencies
- The relative strengths of different lines depend on the temperature of the source
- The width of a line increases with pressure within the source

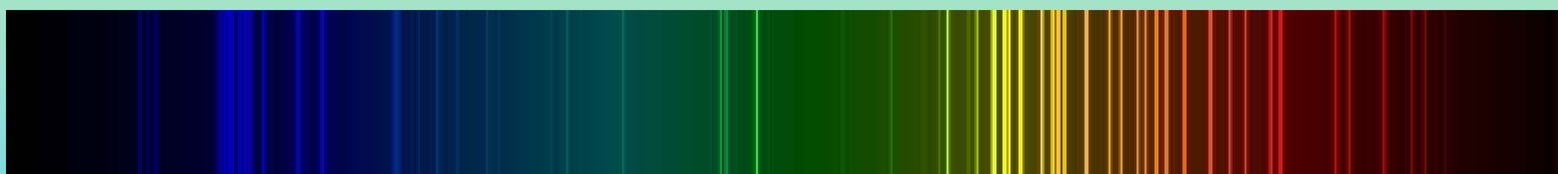


Small section of the solar spectrum

- Different ions of one element all produce different lines

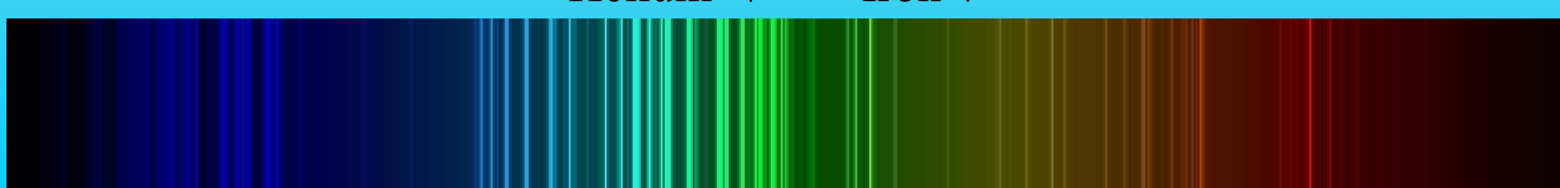
Emission Spectra and Absorption Spectra

- The spectra we have seen so far are **absorption spectra**
  - they are formed by absorbing light from a continuous spectrum
- Emission spectra are bright lines produced by electronically excited atoms



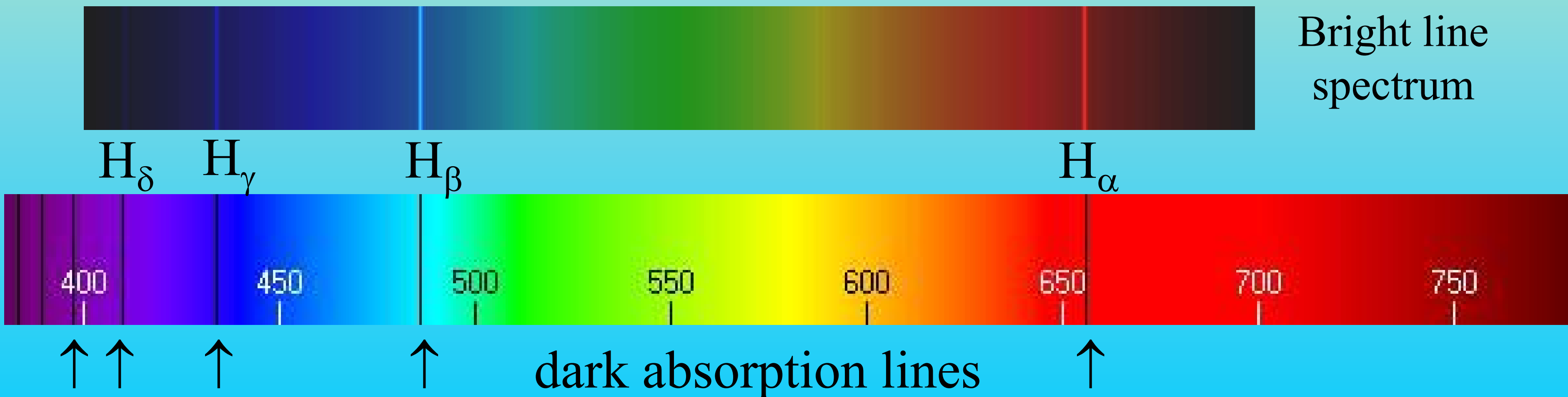
Neon ↑

Helium ↑ Iron ↓



The Hydrogen Spectrum

- Hydrogen is the most common element in the Sun
- Hydrogen forms the simplest spectrum of all elements
- There are 4 lines visible above 400 nm
- Notice the correspondence between emission and absorption spectra
- The visible lines are called the **Balmer series**

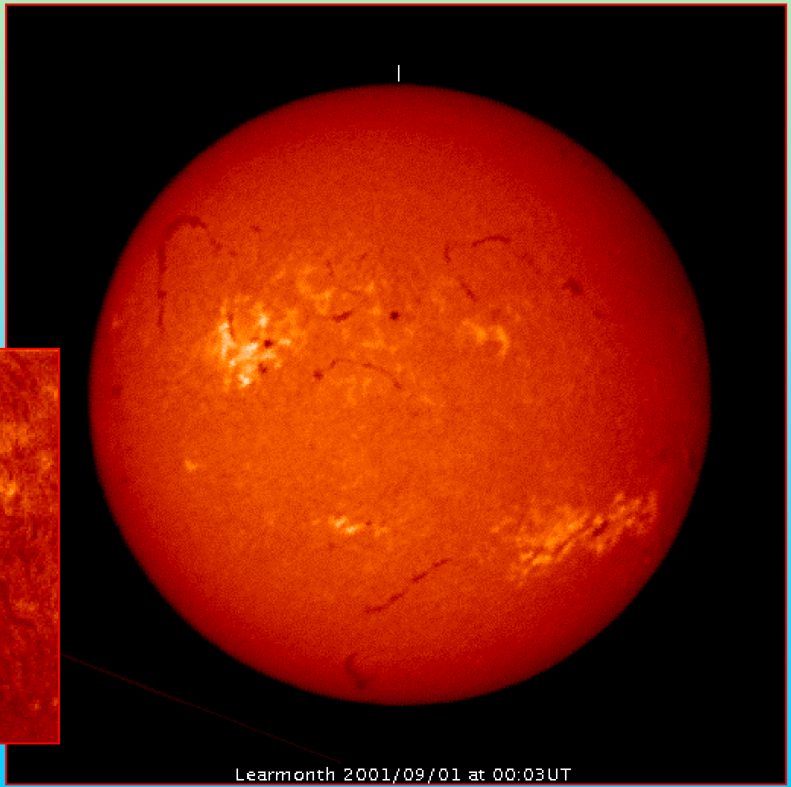


Objects Seen in Hydrogen Light

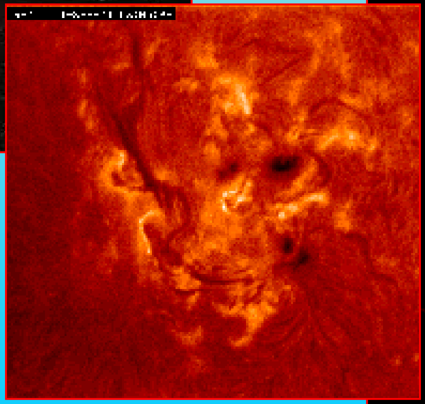
η Carina nebula →

Lagoon nebula ↑

Sun in H_α →

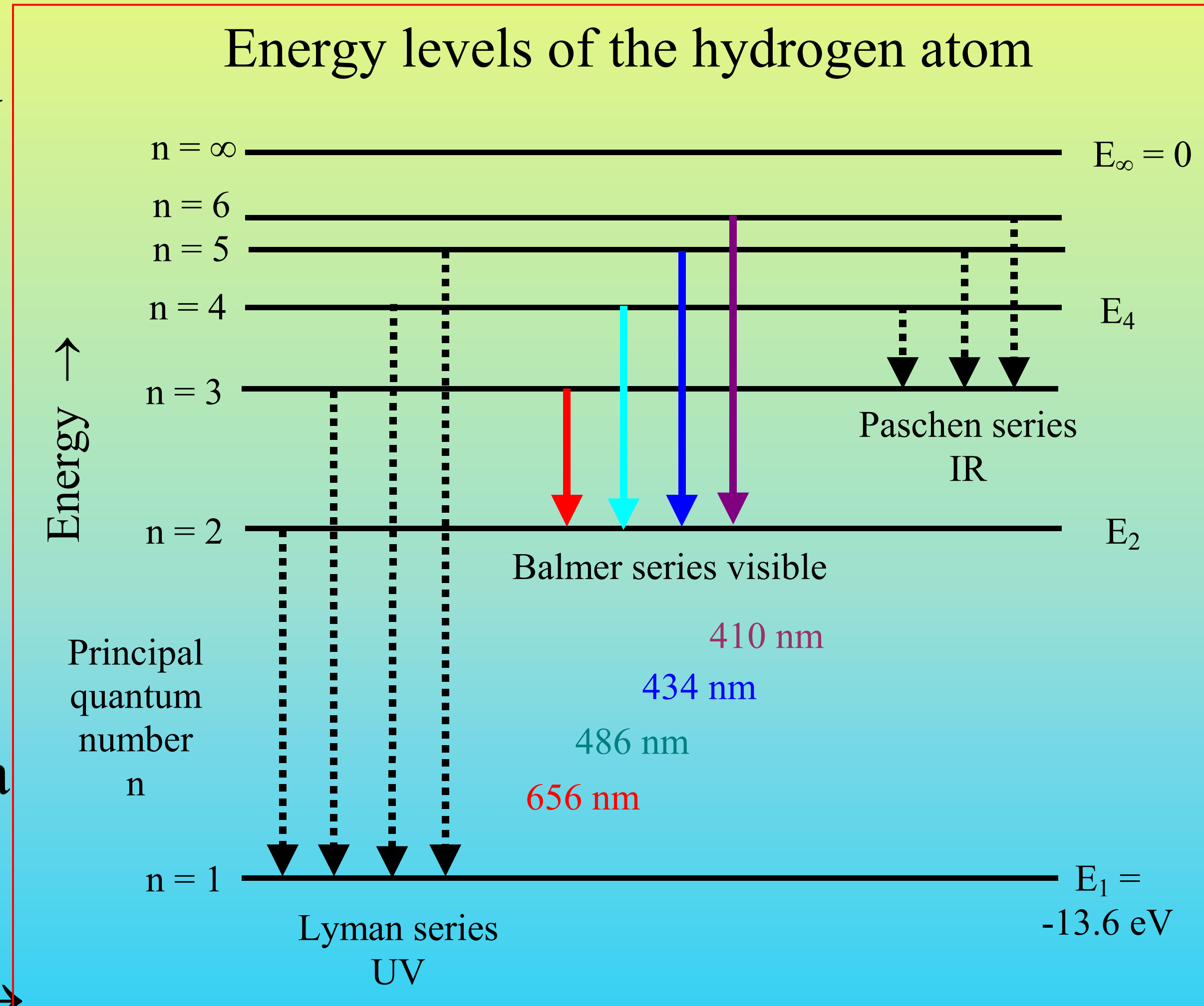


Sunspot with flare in H_α →



Origin of the Hydrogen Spectrum

- Electrons in atoms occupy discrete energy levels
- Energy levels are labelled by **quantum numbers**
- Excited atoms have an electron in an upper, more energetic, level
- Atoms emit radiation when electrons fall to a lower energy level
- Niels Bohr gave the fundamental relation:→



$$hf = E_i - E_k \,,\; f \text{ is radiation frequency}$$

The Quantum Atom

Niels Bohr 1885 - 1962

- Niels Bohr first deduced, in 1913, that the energy levels in atoms were quantised
- He did so by proposing that the angular momentum of orbital electrons could take only integer multiples of $h/2\pi = \hbar$

$$\text{angular momentum} = n\hbar$$

- This introduced the **quantum number** n
- The atomic energy levels are then given in terms of n

$$E_n = -\frac{13.6}{n^2}\ \text{eV}$$

Schrödinger's Wave Equation

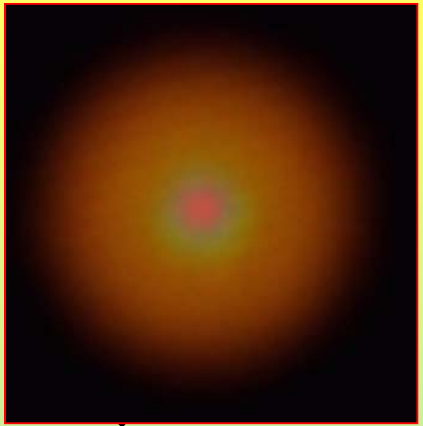
Erwin Schrödinger 1887 - 1961

- Erwin Schrödinger devised **wave mechanics** to describe the quantum nature of the atom (and everything else)
- The atom's **wave function**, ψ, obeys a wave equation
- The wave equation has discrete solutions that give the energy levels of the atom
  - each solution is said to describe a **state** of the atom
- From the values of ψ that are solutions, properties of the atom can be calculated
- In 1 dimension, *x,* ψ obeys :

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2}+U(x)\psi = E\psi$$

Application to the Hydrogen Atom

H atom
is
1 proton
+
1 electron

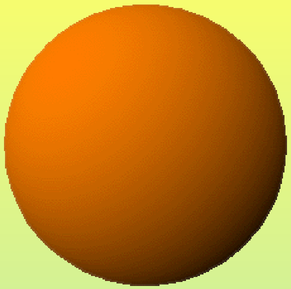


- The **potential**, U, is simply the electrostatic attraction between proton and electron

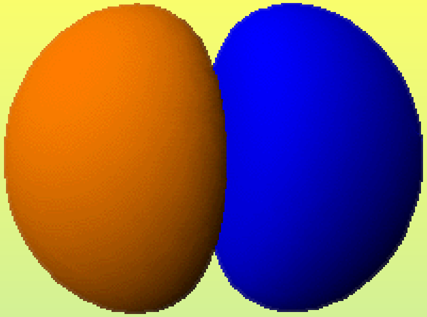
$$U(r) = -\frac{e^2}{4\pi\varepsilon_o r}$$

- The added complexity of 3 dimensions produces 3 quantum numbers that define an atomic state
  - n the principal quantum no. $n = 1, 2, 3, 4, ..$
  - l the total angular momentum quantum no.
    - $l = 0$, **s**
    - $l = 1$, **p**
    - $l = 2$, **d**
    - $l = 3$, **f**
  - m_l the ang. mom. orientation quantum no. $m_l = -l, -l+1, ..., l$

Probability Density

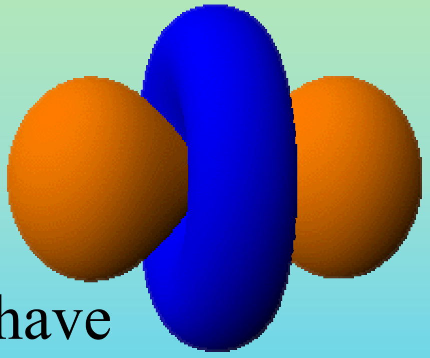


$n = 1, l = 0, m_l = 0$

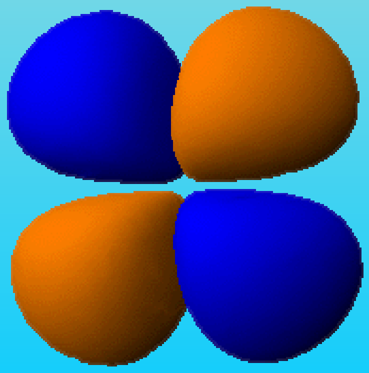


$n = 2, l = 1, m_l = 0$

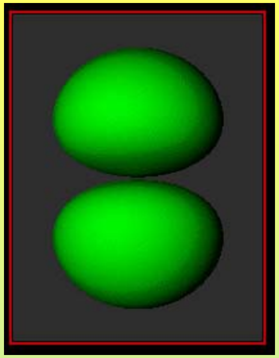
- In a given state, electrons have a varying probability of being at different distances from the nucleus
- The probability at a given place is determined by the value of $|\psi|^2$ at that place
- The resulting picture is still called the electron **orbital** for that state
  - 'orbital' is misleading, e.g. *s* states have no angular momentum
  - the pictures on this page show the shapes, not to scale, of orbitals with different quantum numbers n, l, m_l



$n = 3, l = 2, m_l = 0$



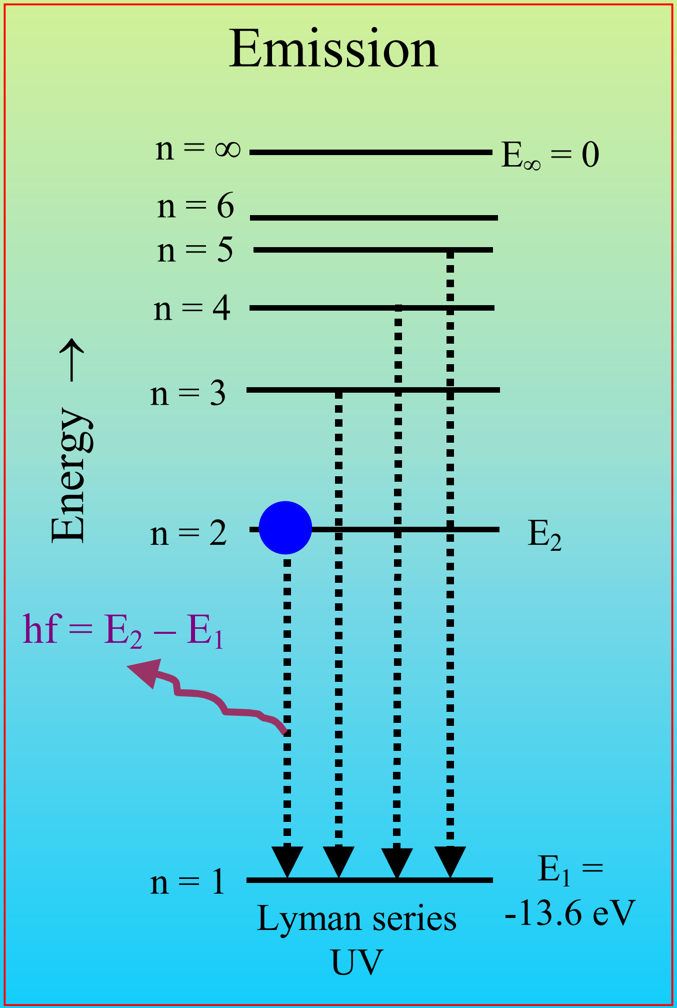
$n = 3, l = 2, m_1 = 2$



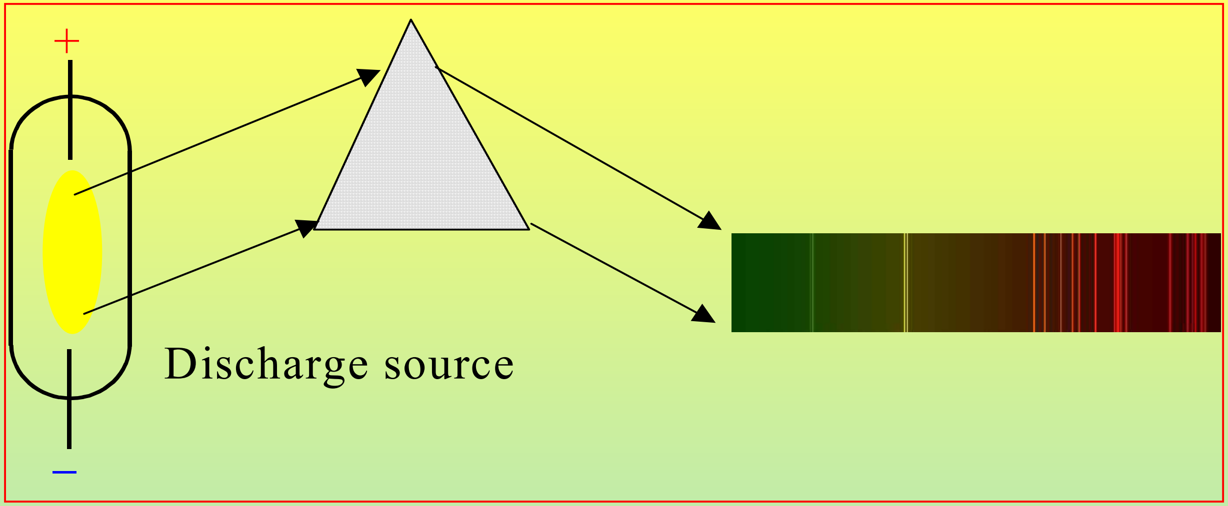
animated

Energy Level Transitions

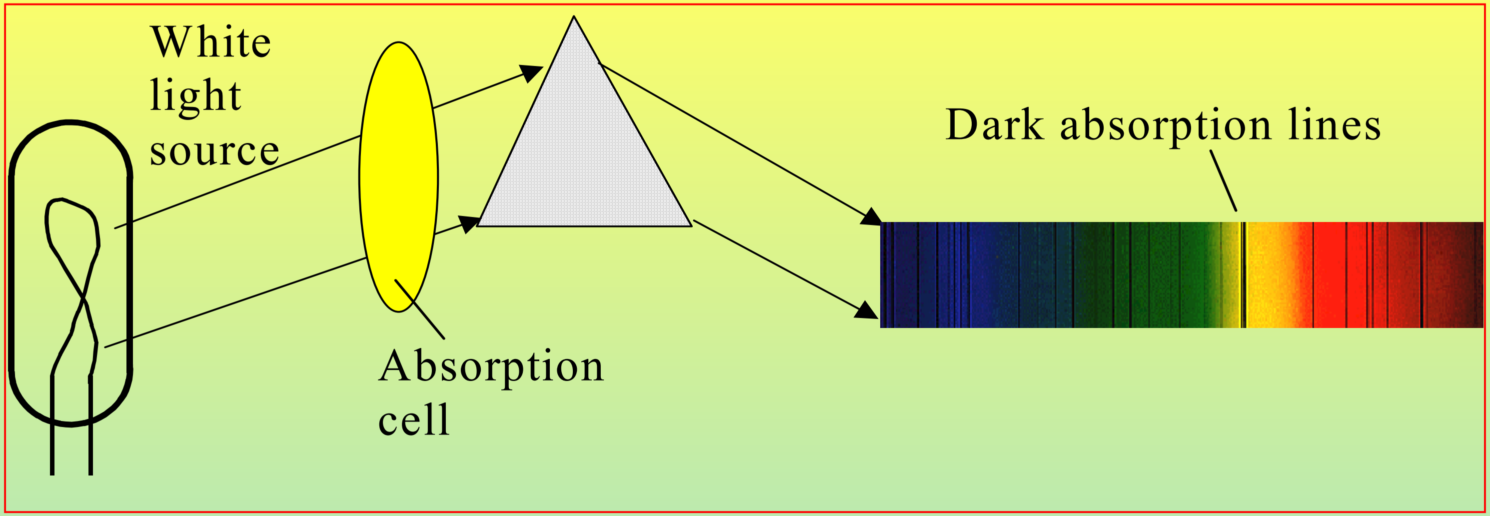
- Emission lines are caused by atoms in an excited state having an electron fall to a lower energy level
- This means the electron wavefunction changes shape
- It might oscillate many millions of times as it emits the light energy
- All possible transitions aren't 'allowed'



Factors affecting the spectrum

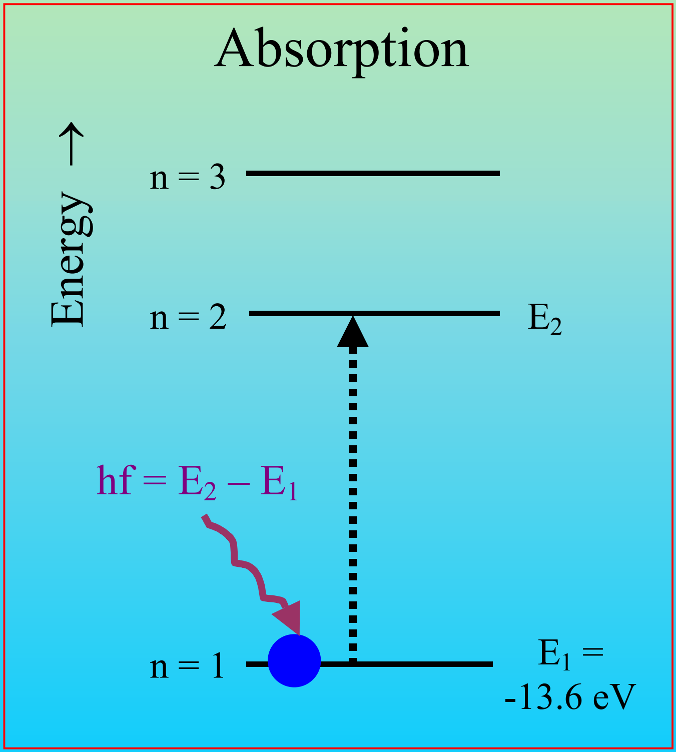


- The number of excited atoms
- Which excited states are populated, and how well
  - you will meet the Boltzmann distribution in later courses, which describes how the population of states depends on temperature
- The transition probability between states
  - this is calculated from the wavefunctions for initial and final states
- The pressure of the emitting substance
  - this is more subtle: higher pressure means atoms close together, which spreads out their energy levels, making the lines broader



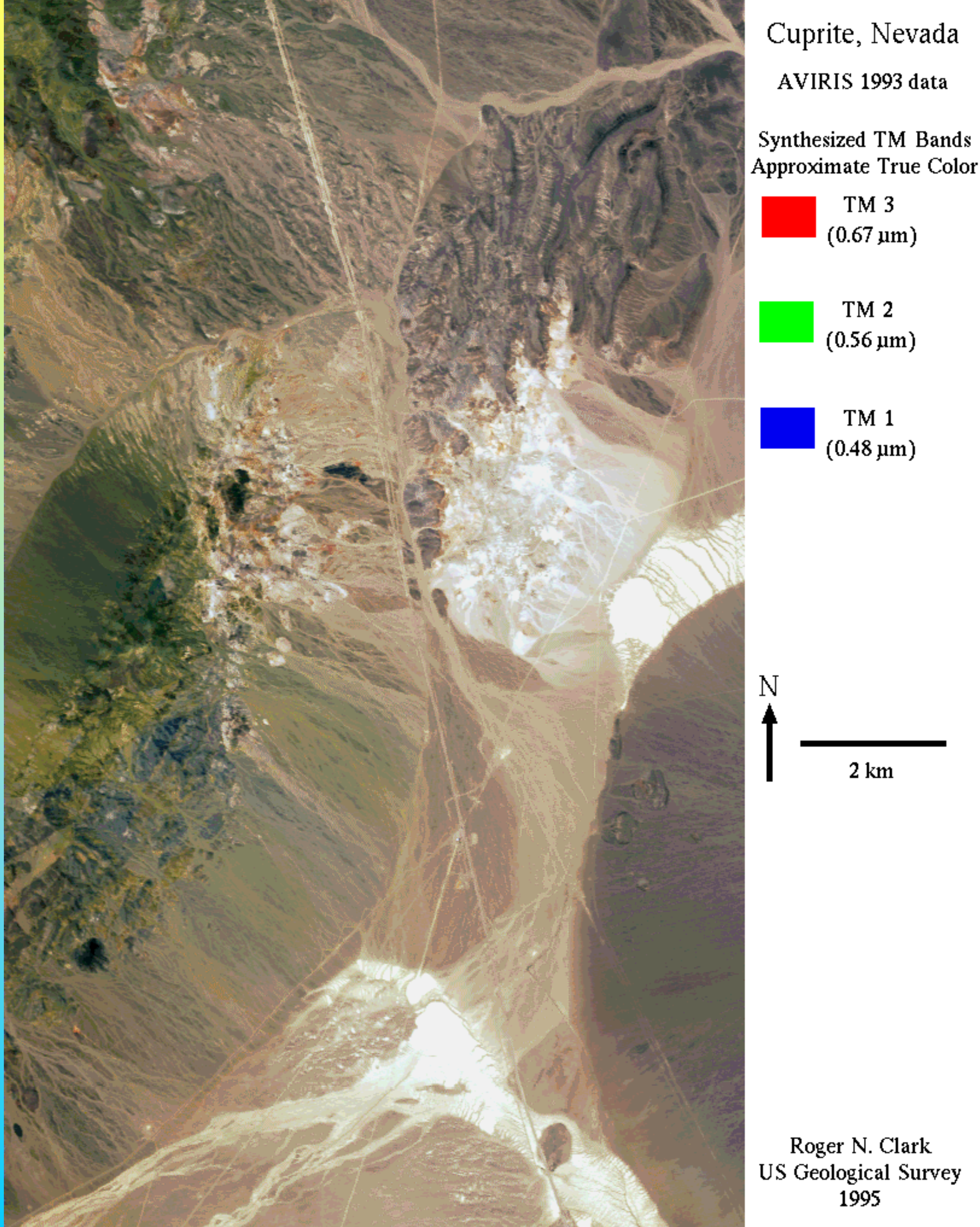
Creating absorption spectra

- White light passes through the sample
- Some incident photons have just the right energy to excite the atoms of the sample
- Light of that particular colour is absorbed



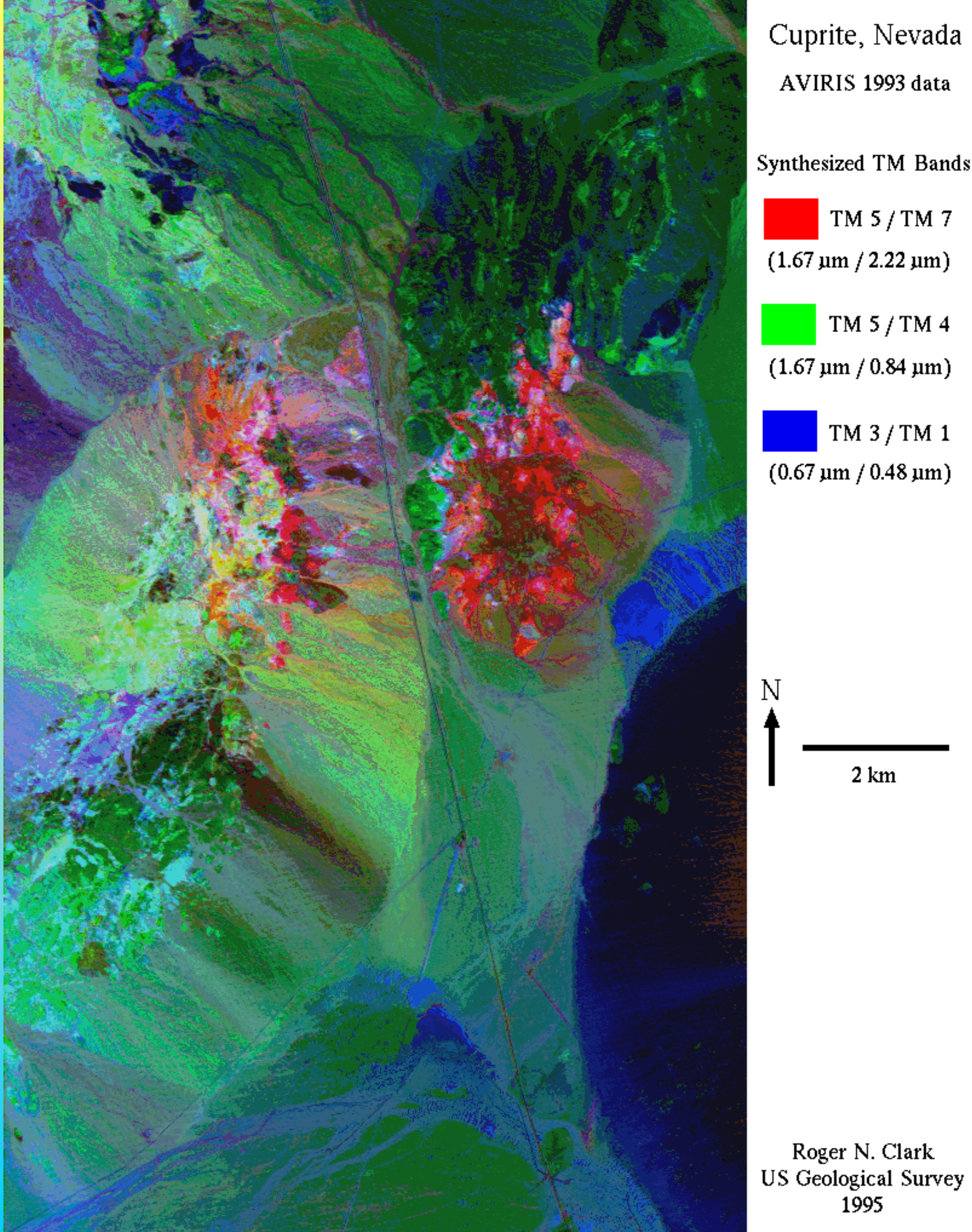
Case Study in Spectroscopic Imaging 1/4

- Images courtesy USGS
- 3-colour visible image
- Area 10.5×17 km



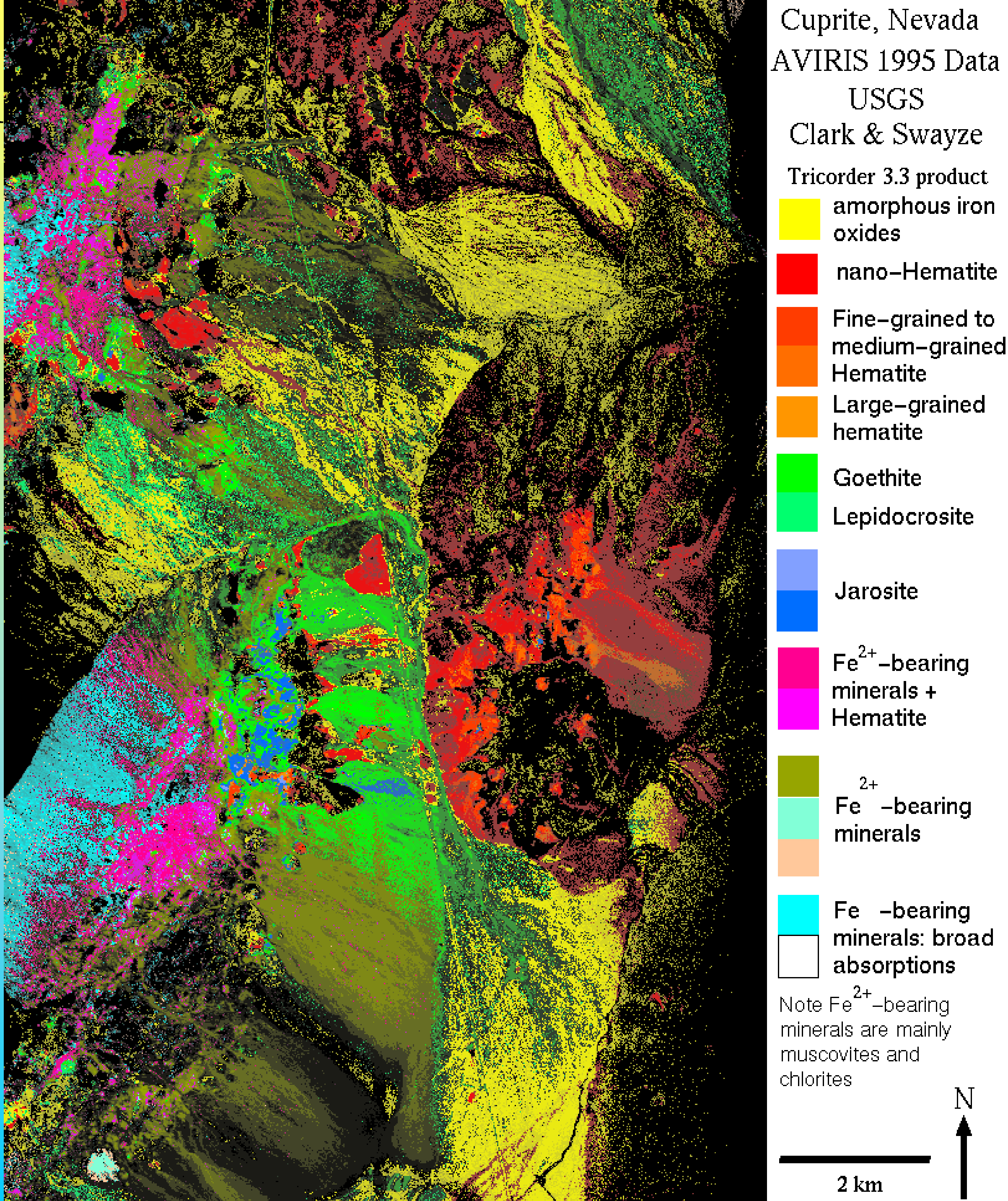
False colour from 6-band Landsat data 2/4

- Broadband filters show up different minerals but there is not enough information to identify minerals



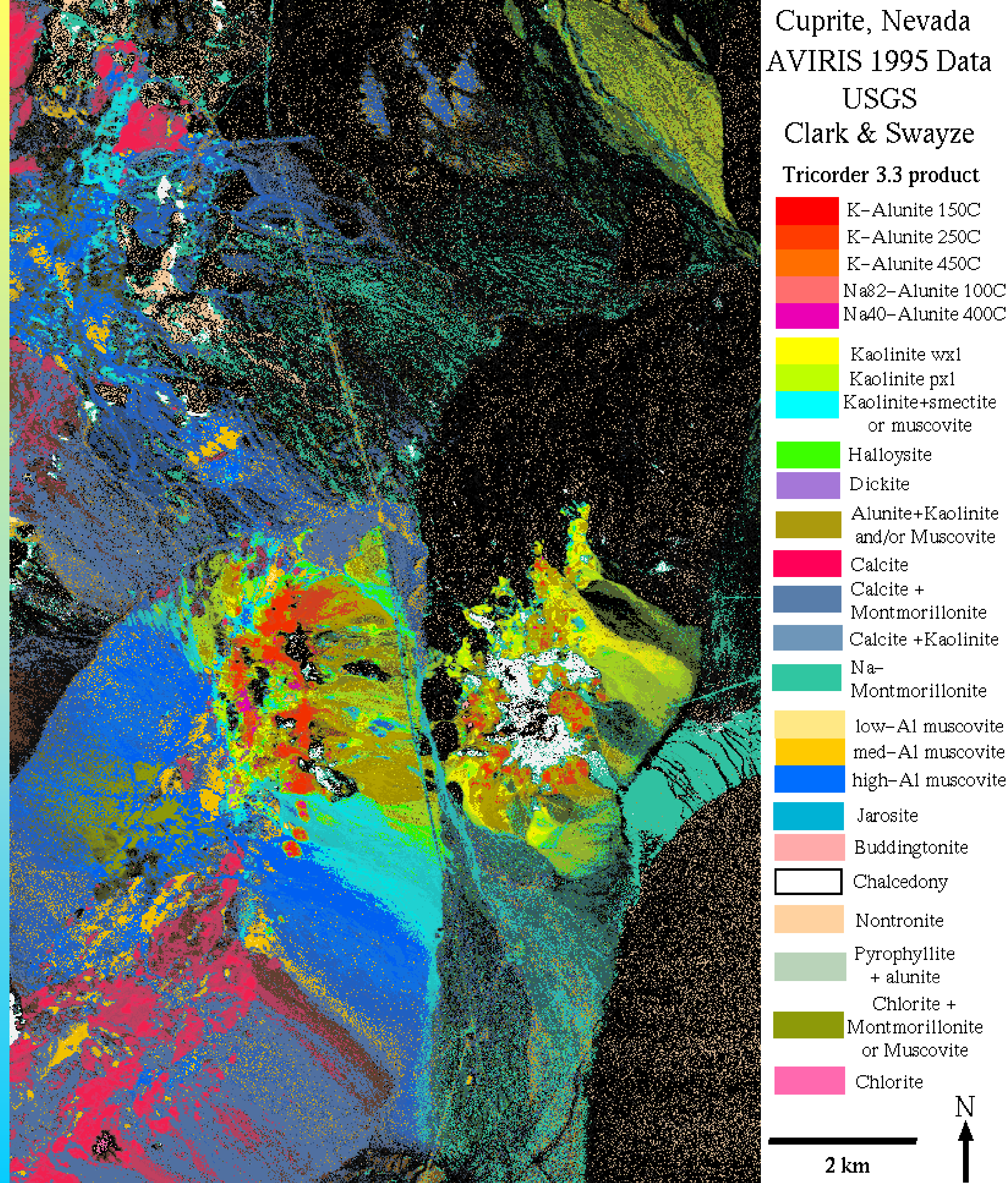
High Resolution Spectroscopy 3/4

- NASA's Airborne Visual & IR Imaging Spectrometer (AVIRIS) has 224 channels from 0.4 μm to 2.5 μm
- The vibrational absorption features (IR) and crystal structure features allow mineral identification

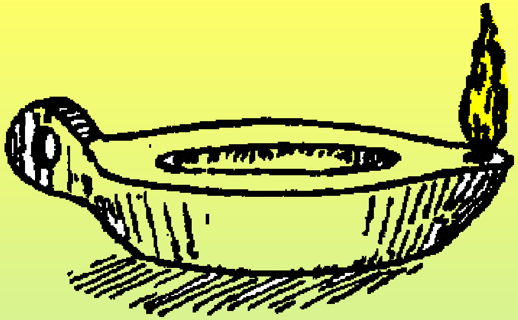


Fine Detail of the Mineralogy 4/4

- Electronic absorption features of Fe^{2+} and Fe^{3+} minerals in range 0.4 µm to 1.2 µm are very sensitive to crystal structure, making highly detailed remote sensing maps possible



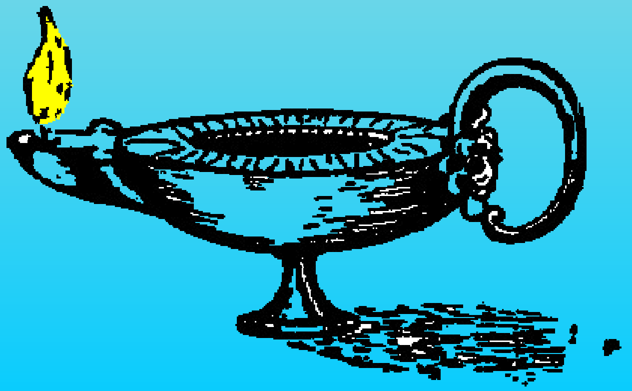
Making Light



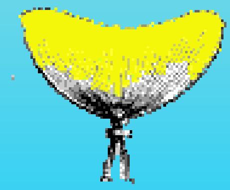
Roman oil lamp

- The Sun - nobody does it better
  - power source: nuclear fusion
- Firelight, oil light, candles, gaslight
  - all emit continuous spectra
  - temperatures not much more than 1500°C
  - Planck's law predicts the radiation produced

candle

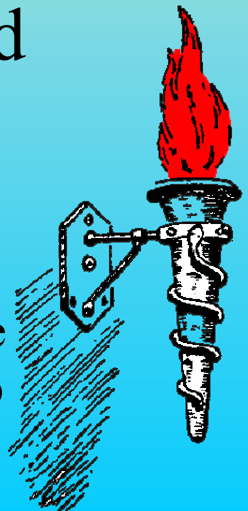


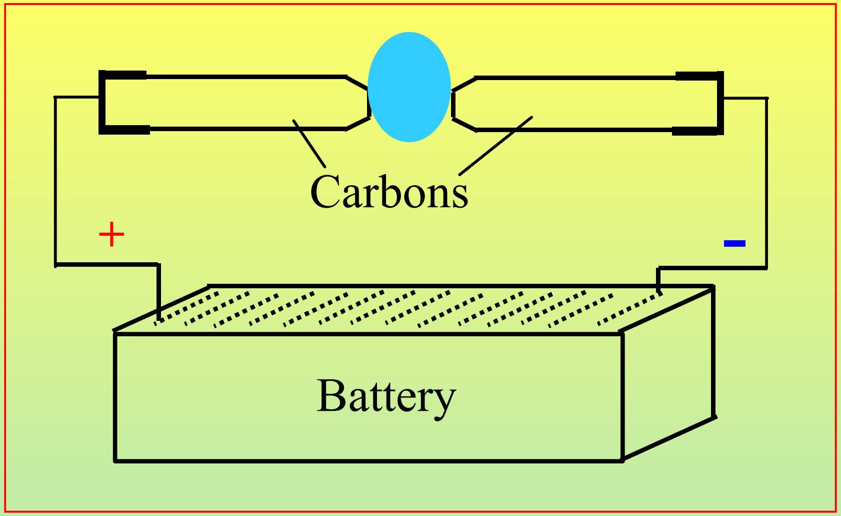
Bronze oil lamp



Fish-tail gas light

Flare lamp





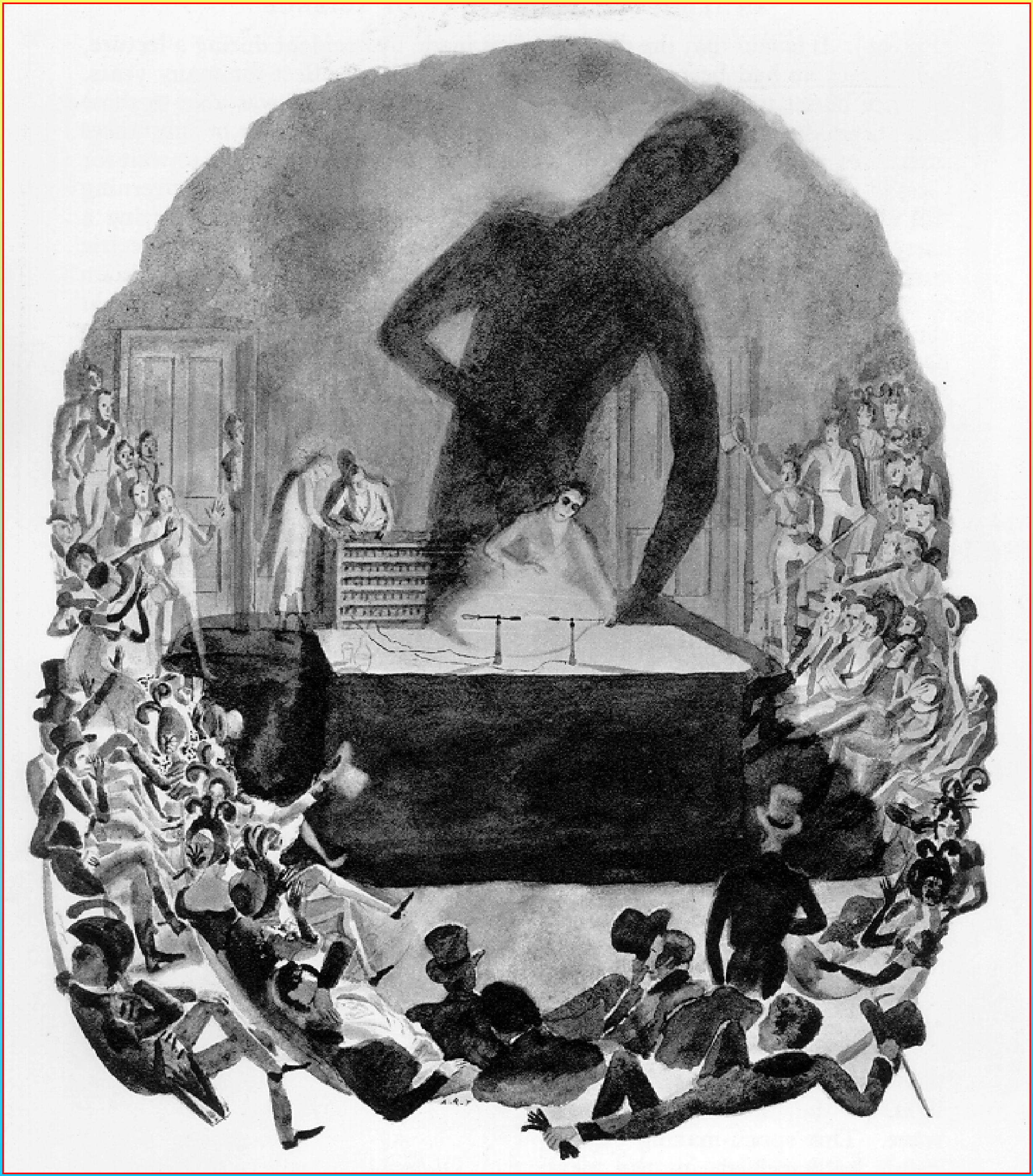
The Arc Lamp

Humphry Davy
1778 - 1829

- Passing a current through two rods of carbon, an arc of brilliant light appears when they are separated
  - discovered by Humphry Davy in 1808
  - he used a current of ~5 A and at least 30 V
  - more recent lamps ~10 A at 50 V
  - hardly any commercial development took place over the next 60 years, because of the expense of batteries

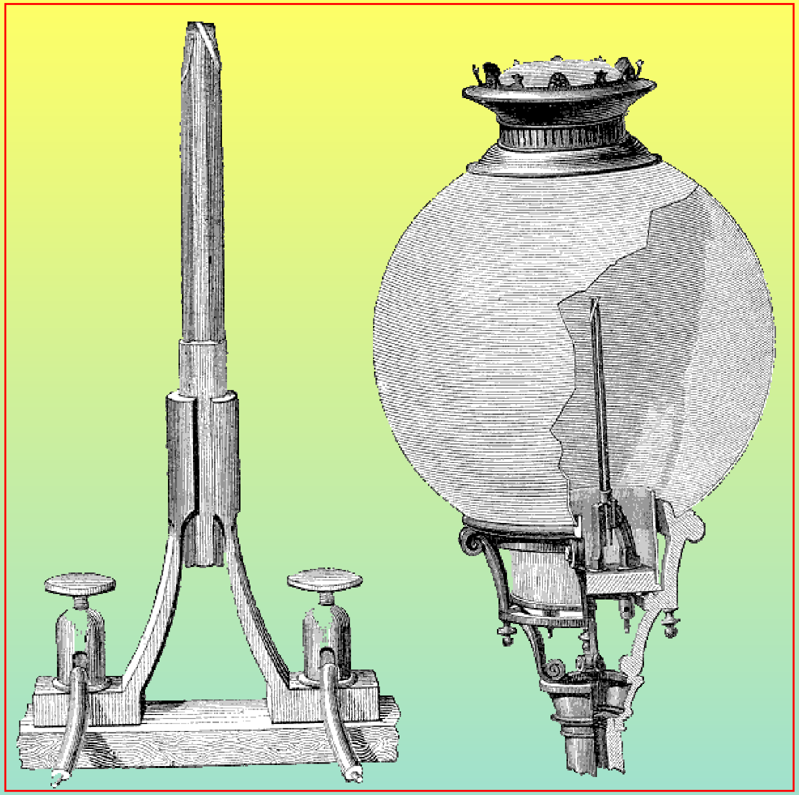
Davy exhibiting the arc lamp in 1808

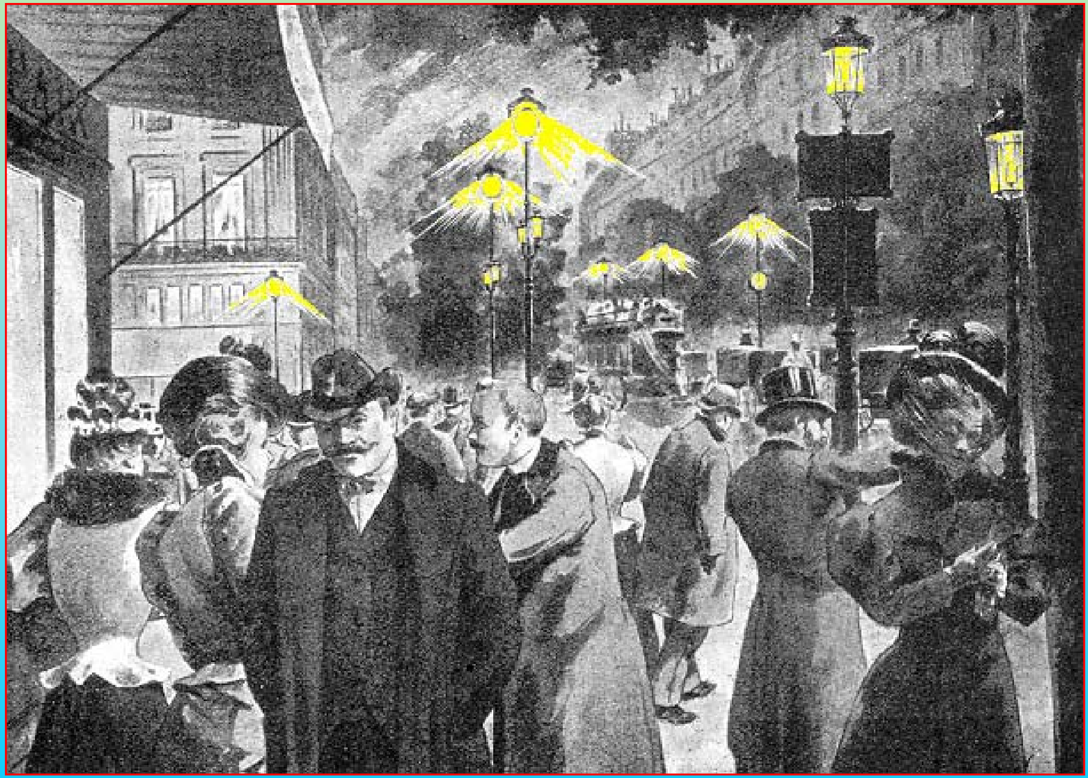
- Davy was Professor and public lecturer at the Royal Institution in London
- Picture by A. R. Thomson, courtesy F. Sherwood Taylor *An Illustrated History of Science*, Heineman 1955



Arc Lamps Become Useful

- In the Jablochkoff candle, 2 parallel carbons were separated by paste



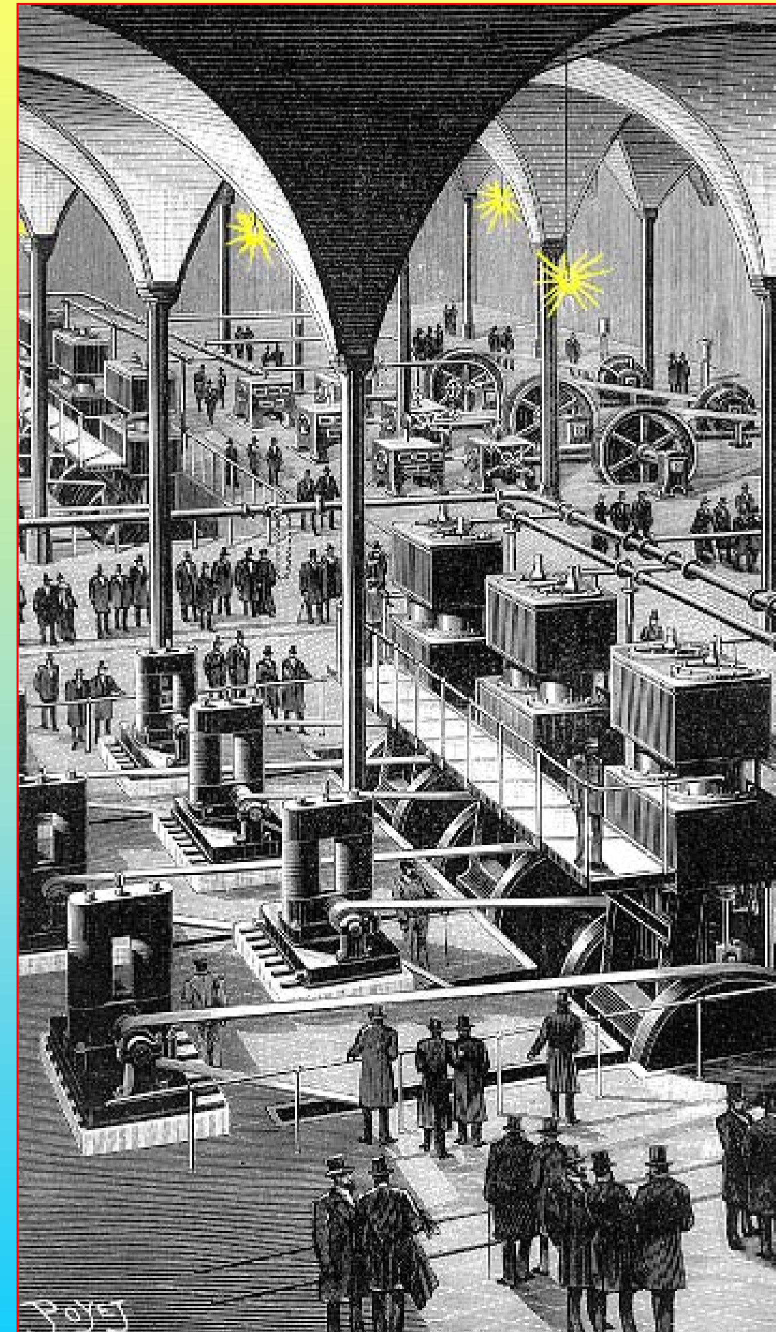


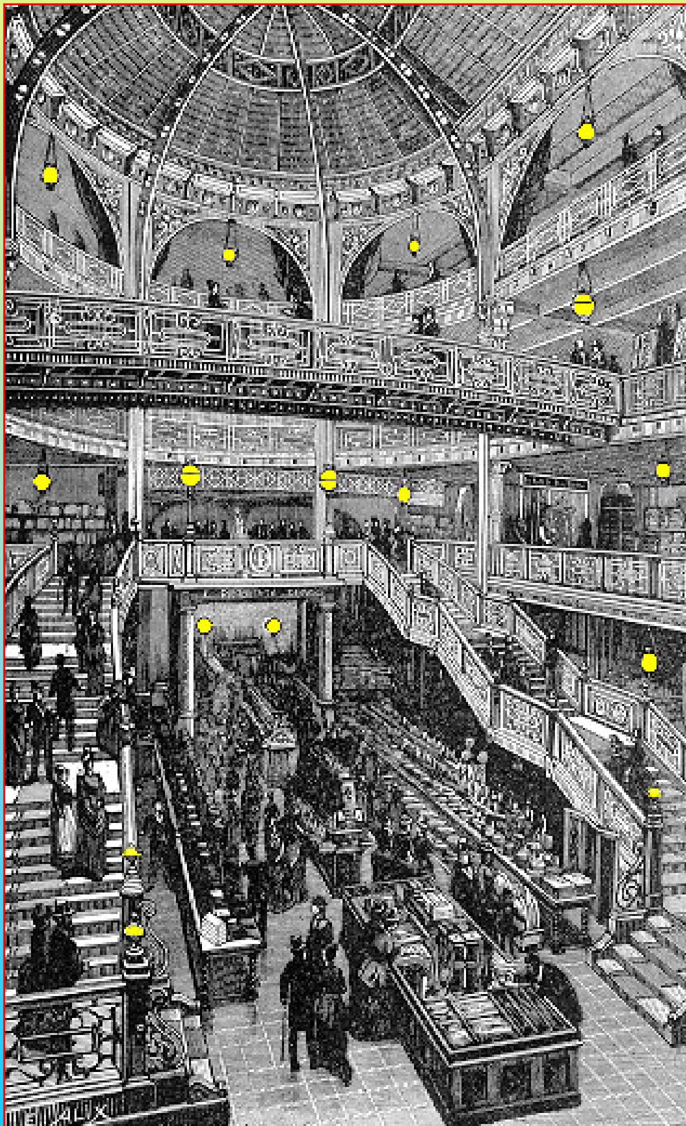
- Streets were successfully lit from the 1880s
- Arc lamps burn at ~3300°C

Lighting in the Boulevards of Paris

Dynamos Provide Public Electricity

Municipal power station at Halles, Paris in 1889 →





← *Magazin Printemps* lit in 1882 with 300 Jablochkoff candles and 255 incandescent lamps

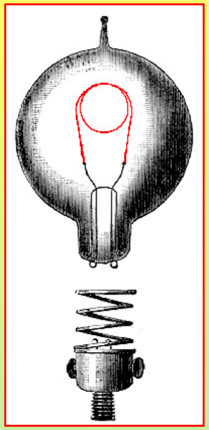
T A Edison

- Electrical generators
- Phonograph
- Incandescent electric lamp
- Much more

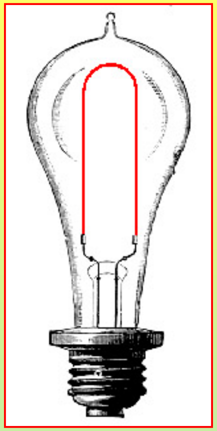
Thomas Alva Edison 1847 - 1931

Incandescent Lamp

- Independently developed by Thomas Edison and Joseph Swan in 1879
- They took out a combined patent to form the Ediswan Company

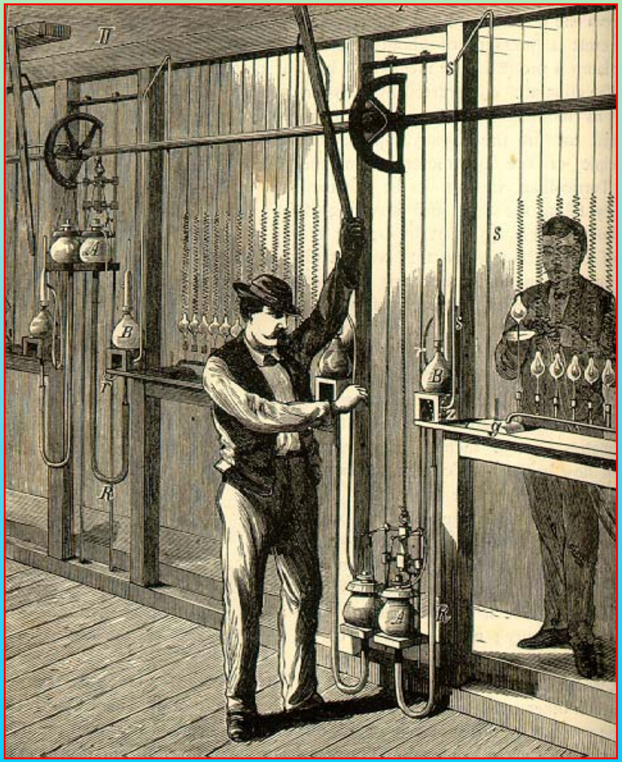


Swan

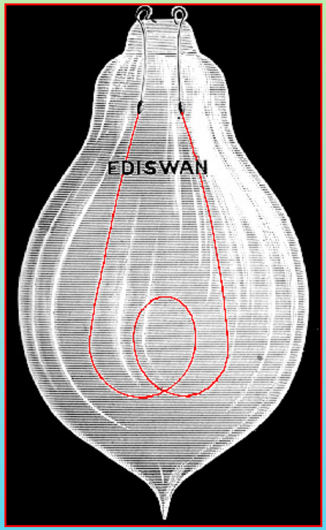


Edison

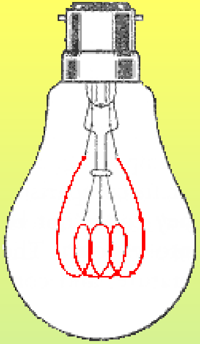
- The development was made possible by the Sprengel mercury vapour vacuum pump



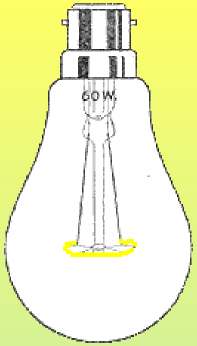
Sprengel high vacuum pump



Ediswan



Light-bulb Physics



- ‘Glow lamps’ (carbon filament lamps) operated at temperature ~1900°C; modern lamps operate ~2500°C
- A 16 candle power glow lamp consumed 60 W; a modern lamp of same light output (200 lm): ~12 W
- Lowest voltage glow lamps were 55 V
- **Metal filaments** developed around 1900 had lower resistance than carbon
  - they had to be longer
  - short filaments could run off low voltages, introducing torch lamps, electric bicycle lamps, etc.
  - more efficient light producers with a longer life

‘Modern’ Light Bulbs

Langmuir and T A Edison
in 1922

- Invented by Irving Langmuir in 1913
- Spiralised tungsten filaments
  - acts like a short length but has large resistance
  - reduced evaporation of tungsten
  - concentrates evaporation at end of bulb
- Filled with argon/nitrogen mixture
  - cools filament, helping to avoid hot spots

↑ Filament before spiralising

Spiral filament

Resurgence of gas lighting

- Carl Auer von Welsbach gas mantle made from cotton fabric impregnated with thorium oxide and 1% cerium oxide
- Upon being lit the fabric burnt away and the oxides fused into a hard but fragile mantle
- The mantle transformed gas lighting, producing incandescent light to rival that of electricity
- These mantles evolved into the modern versions used in Calor and other gas installations
- Reason for their success
  - hotter than a free flame
  - optically dense, i.e. presents a large area of opaque hot source
  - the oxides luminesce

Welsbach gas mantle

Gas Discharge Tubes

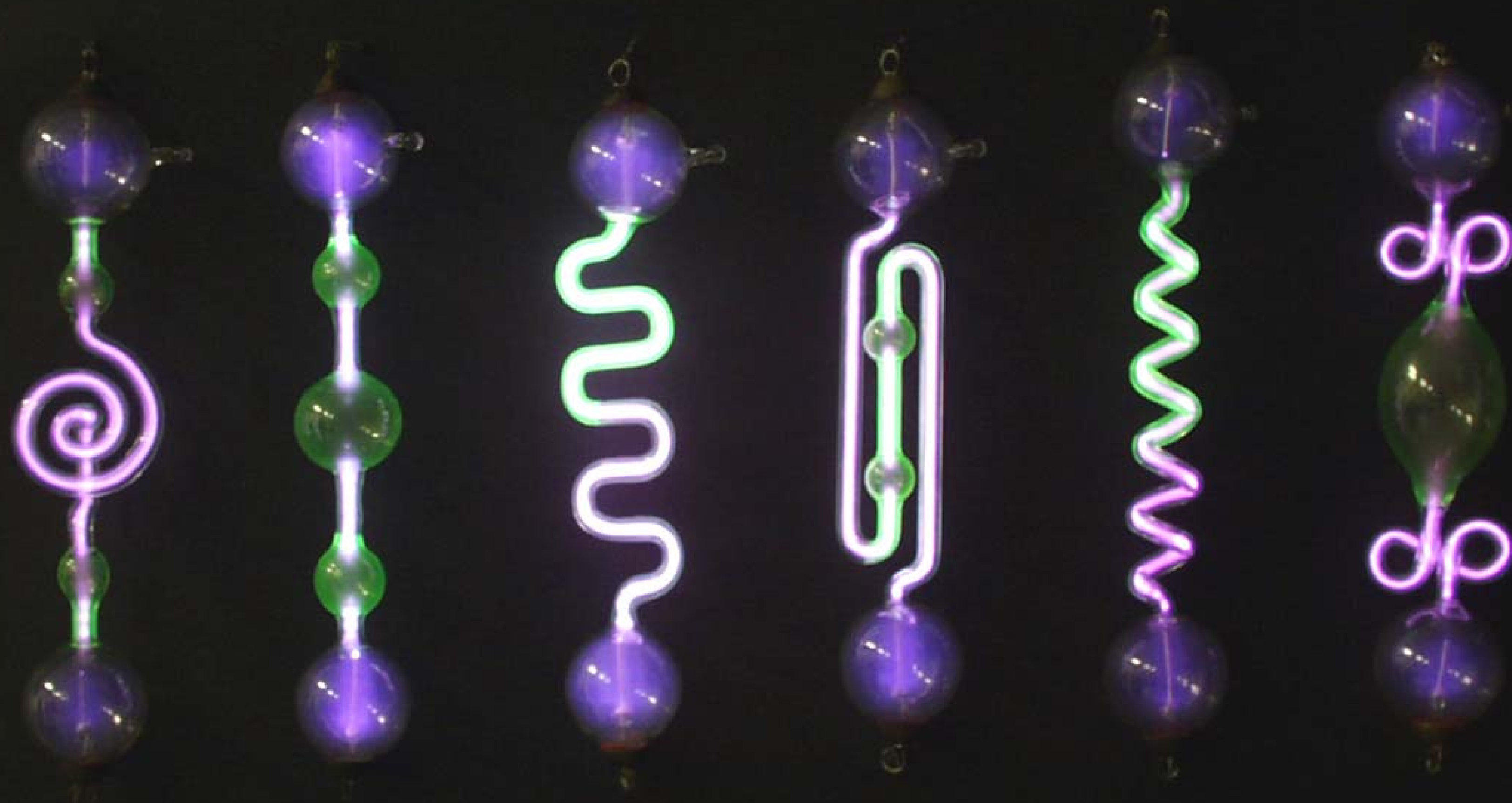
Gassiot, 1860s

- Investigated for the physics of how gases behave at low pressures when electrically excited
  - Gassiot (1860s), Spottiswode, Müller, Geissler, De la Rue → Crookes → discovery of electrons → high vacuum tubes
  - led to discovery of X-rays
  - spectroscopy of low pressure discharges
  - discharge tube lamps

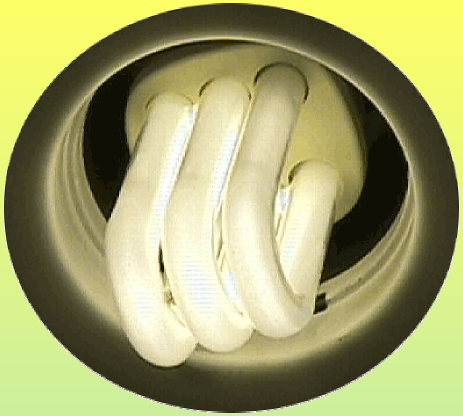
De la Rue, 1870s

19^{th} century Geisler Tubes

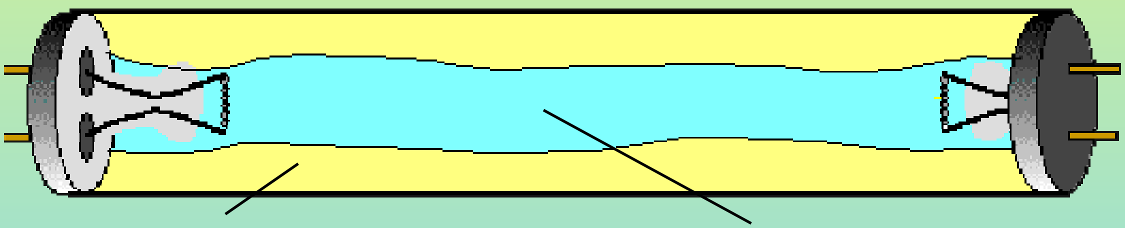
From the Natural Philosophy Historical Collection



The Modern Fluorescent Light



- The underlying principles



- mercury (Hg) discharge inside creates a plasma
- excitation of Hg atoms creates spectral emission, mainly in UV
- phosphorescent coating re-radiates light in visible
- choice of phosphor determines colour

Plasma Screens

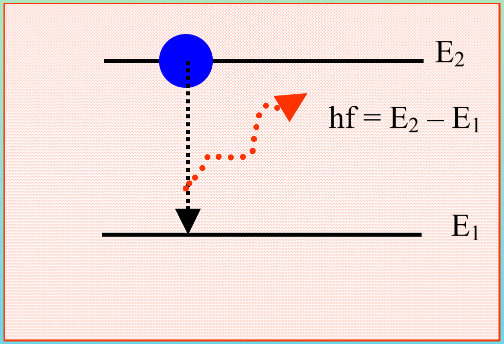
Queen Mother Library
plasma screen display

Laser light

- LASER – Light Amplification by Stimulated Emission of Radiation
- Common lasers around are solid state lasers
  - CD readers, CD players, laser pointers, etc.
- Lasers met with in our labs and in many instrument applications are He/Ne lasers
- Laser light:
  - very intense
  - highly directional
  - coherent, across and along the bea

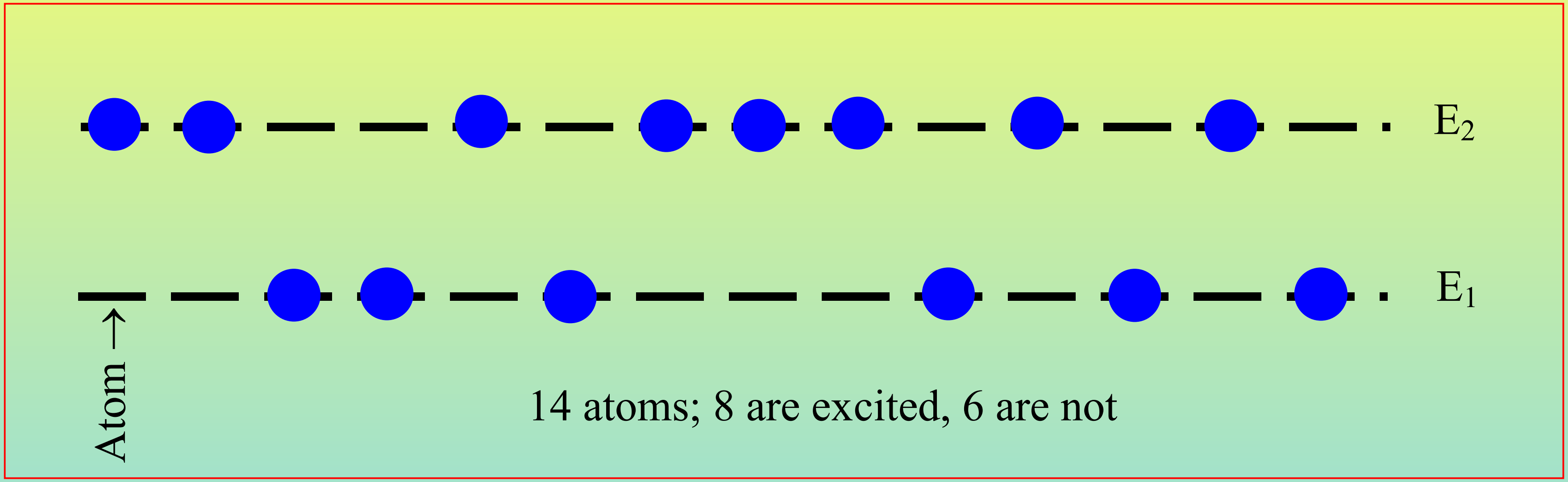
Stimulated emission

- In the presence of electromagnetic radiation of just the right frequency, an excited atom can be stimulated to give up its energy and emit a photon
  - the emitted light is *in phase* with the stimulating radiation



- Under normal circumstances, this is very unlikely to happen with visible light
- To make it happen, the background radiation must be much more than simple blackbody radiation

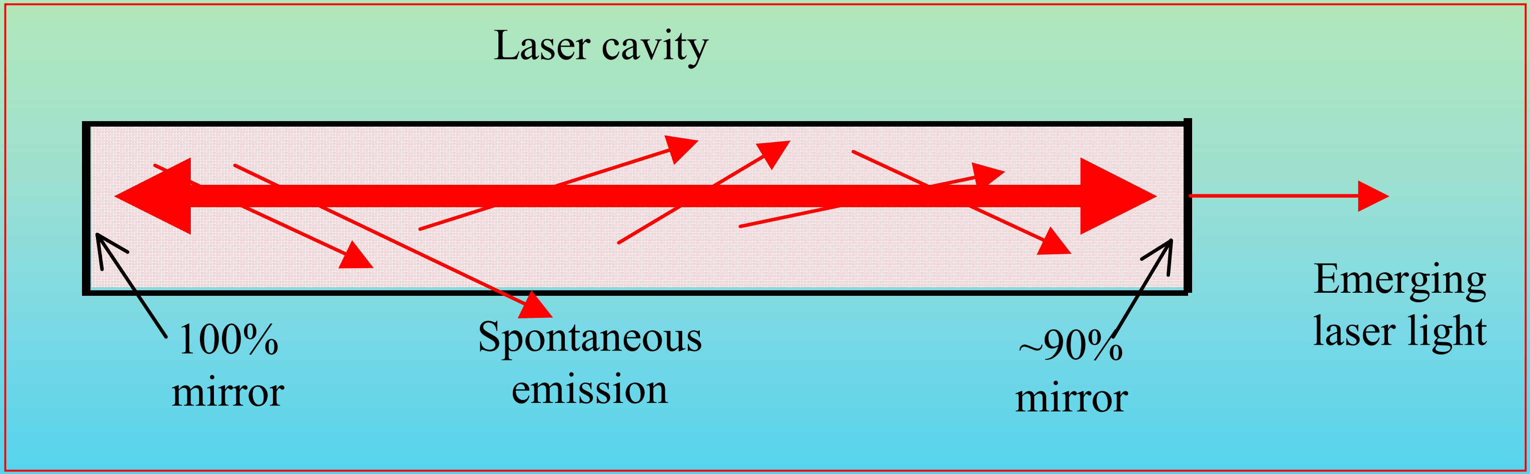
Population inversion



- With a collection of atoms, when more are excited than are not, the population is said to be 'inverted'
- When radiation is present, stimulated emission exceeds absorption when there is population inversion
- Part of making a laser is to generate population inversion

A simple laser cavity

- Lasing takes place in a 'cavity'
- A simple cavity has parallel reflectors at either end, one transmitting a small fraction



- Only the light parallel to the axis builds up enough radiation to create stimulated emission

The working of a He/Ne laser

- Helium atoms are excited by electrical discharge into a metastable state from which they don't radiate
- When they collide with Ne atoms this excess energy is transferred to the neon atoms, exciting them to a metastable state at the same energy
- This builds up a 'population inversion' in the neon