# Course notes - reminder

- http://zuserver2.star.ucl.ac.uk/~rwesson/PHAS1511

# Units reminder

perception that climate change is way down the road in the future and it affects only remote parts of the world," she told a press conference today. "This report says climate change is happening now. It is happening in our own back yard."

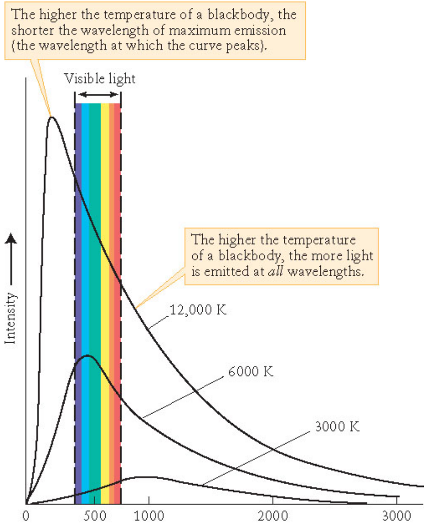
Average temperatures in the US have risen by1.5F (-17C) over the last 50 years, the report said. Rainfall in major storms has increased 20% over the last 100 years - with the heaviest downpours in the north-east. Sea levels have risen up to eight inches along some parts of the east coast.

The consequences of those changes are rippling through every region of the US between Alaska and Hawaii - from the disruption of salmon

# Units reminder

- Watch out for the difference between the **size** of the unit, and the **zero point** of the scale
- $1\text{K} = 1^\circ\text{C} = 1.8^\circ\text{F}$
- $273.15\text{K} = 0^\circ\text{C} = 32^\circ\text{F}$

# Black body radiation



# Black body radiation

- There is a very simple relation between the temperature of a black body, and the wavelength at which its emission will peak:

$$\lambda_{peak} = \frac{0.0029m}{T}$$

- This relationship was discovered by Wilhelm Wien in 1893, and is called Wien's Law.

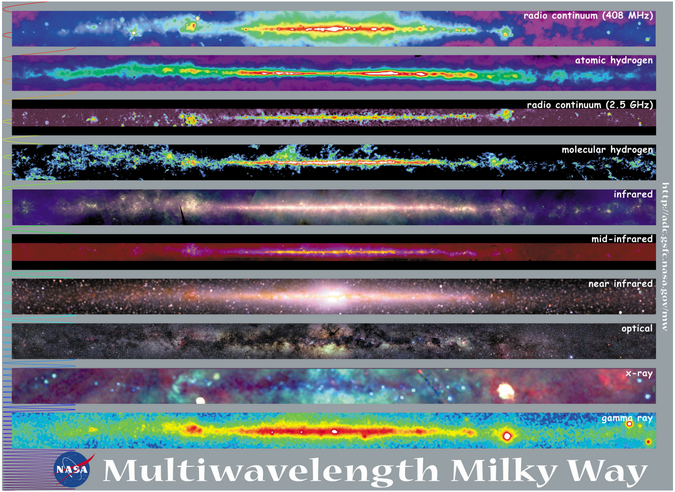
# Astronomical objects

- Different types of object emit different types of radiation, and so the different parts of the electromagnetic spectrum each reveal a different facet of the universe.
- **Radio waves** are generally emitted by very cold gas. The gas between the stars emits radio waves.
- **Microwaves** are emitted by cold dust and also by the universe itself as a consequence of the Big Bang.
- **Infrared** is emitted by warm gas and dust, and is particularly useful for studying the births and deaths of stars.

## Astronomical objects

- **Visible light** is emitted by hot objects like stars.
- **Ultraviolet light** is emitted by the hottest, most massive stars.
- **X-rays and gamma rays** re emitted by extremely hot material (millions of K!). They tell us about some extreme environments matter spiralling into a black hole, violently exploding stars, and the gas surrounding clusters of galaxies all emit strongly at these wavelengths.

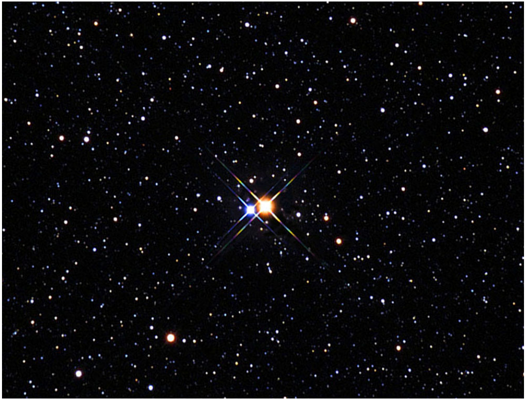
# The galaxy at many wavelengths



# Black body radiation

- The emission from stars is quite similar to the emission from black bodies. This means that we can estimate their temperatures from the shape of their spectra.
- The Sun's surface is at a temperature of about 5,800K, and black bodies with this temperature emit radiation with a peak wavelength of about 550 nm.
- Not at all coincidentally, this is in the middle of the range of wavelengths that our eyes can perceive.

# Black body radiation



- $\beta$ Cygni: the orange star has a temperature of 4000K; the blue one is much hotter at about 30,000K

# Black body radiation

- Wien's law tells us the temperature of a black body, if we know the wavelength where its emission peaks.
- Another very useful equation related the total amount of energy emitted to the temperature of a spherical black body, and its area.
- $F = \sigma T^4$
- F is the energy emitted per square metre of surface area. $\sigma$ is a constant. So, if you doubled the temperature of an object, you would increase the amount of energy it emitted by a factor of 16.
- This equation is called the Stefan-Boltzmann Law, after the two physicists who discovered it.

# Wien and Stefan-Boltzmann - example

- $\beta$ Cygni: the *cooler* star is also *brighter* - it must therefore be *larger*

# Wien and Stefan-Boltzmann - example

- Sirius is the brightest star in the sky. Its spectrum peaks at a wavelength of 290nm. So, what is its temperature?

$$\lambda = 0.0029 / T$$

- So,

$$\begin{aligned} T &= 0.0029/\lambda \\ &= 0.0029/290 \times 10^{-9} \\ &= 10,000K \end{aligned}$$

# Wien and Stefan-Boltzmann - example

- How much more energy does Sirius emit per square metre of its surface than the Sun does?

$$\begin{aligned} \frac{F(Sirius)}{F(Sun)} &= \frac{T(Sirius)^4}{T(Sun)^4} \\ &= (10,000/5,800)^4 \\ &= 8.8 \end{aligned}$$

# The nature of light – Part II

- These equations are extremely useful in understanding astronomical objects. However, they caused physicists huge problems in the late 1800s, because they could not be understood within the framework of light being a wave phenomenon.
- Max Planck found that he could explain the shape of black body radiation, if he assumed that light was made up of particles.
- Albert Einstein used this idea to explain the photoelectric effect – light striking a metal can cause the metal to emit electrons.

# The nature of light – Part II

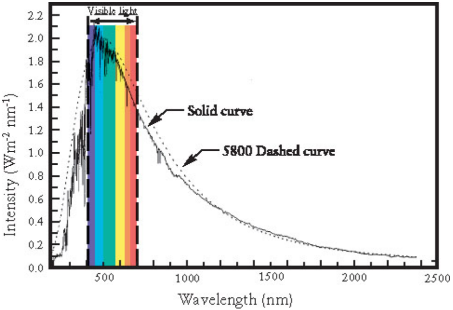
- If you increase the *brightness* of the light, the energy of the electrons stays the same. But if you increase the *frequency* of the light, the electrons move faster.
- This doesn't make sense, if light is a wave. But it makes perfect sense if light is made of particles.
- The photoelectric effect proves that light is made of particles. But Young's two-slit experiment already proved that light is a wave phenomenon.
- In fact, light behaves both as a particle, and a wave, at the same time. The higher the *frequency*, the more *energy* the light particles (photons) are carrying:

$$E = hf$$

- (h = Planck's constant = $6.634 \times 10^{-34}$J/Hz)

# What EM radiation can tell us

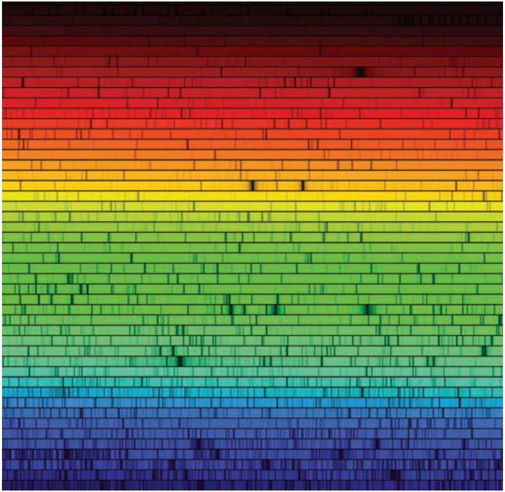
- Using Wien's law, we can use the fact that stars are quite like black bodies to estimate their temperatures. But so far we don't know anything about their composition.
- Stars are not exactly like BBs:



# What EM radiation can tell us

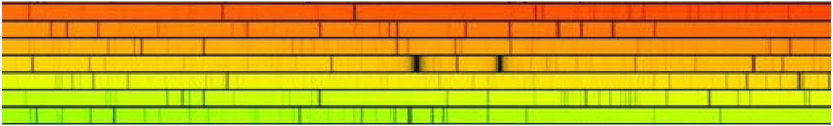
- The difference between a stellar spectrum and a black body can tell us about what the star is made of.
- Joseph von Fraunhofer made a major advance in astronomy by examining the spectrum of the Sun at very high magnification. He found that it was full of dark lines.

# What EM radiation can tell us



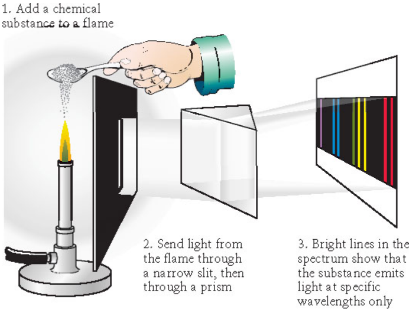
# What EM radiation can tell us

- The meaning of the dark lines became clear from **flame tests** – if you throw some salt into a flame, you will see that you get a bright yellow light.
- If you analysed that light, you'd find that it was being emitted at exactly the same wavelengths as the two particularly dark absorption lines in the yellow part of the solar spectrum.



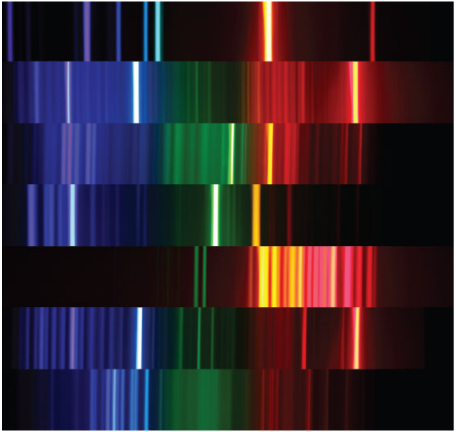
# What EM radiation can tell us

- 19th century chemists Gustav Kirchhoff and Robert Bunsen discovered that each element, when burned in a flame, only gives off light at certain discrete wavelengths.



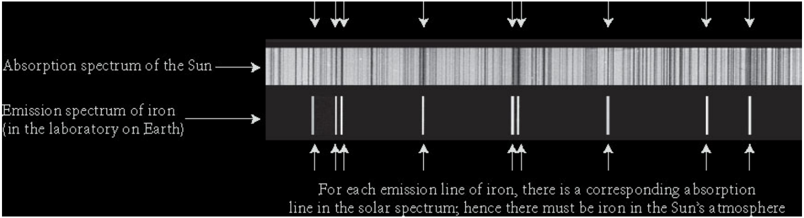
# What EM radiation can tell us

- The wavelengths at which light is emitted are different for different elements:



# What EM radiation can tell us

- Clearly, the two dark lines in the yellow part of the Sun's spectrum must be caused by sodium in its atmosphere.
- Other lines correspond with the light emitted by other elements in flame tests, and so those elements must also be present – for example, iron:



# Discovering new elements

- Kirchhoff and Bunsen carried out flame tests on mineral water vapour. They observed spectral lines in the blue and in the red part of the spectrum.
- They isolated the elements responsible and found that they were new to science. They called them caesium (from the latin for blue) and rubidium (from the latin for red).

# Discovering new elements

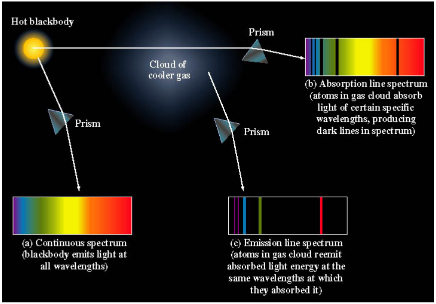
- When observing a total solar eclipse in 1868, Norman Lockyer observed a spectral line coming from the Sun's atmosphere, which didn't correspond to any element so far observed in the lab.
- He proposed that the line was due to a new element, which he called helium (from the Greek Helios: Sun).
- He was proved right: helium was discovered on Earth in 1895 (it is given off by the radioactive decay of Uranium)

# Kirchhoff's laws

- Clearly, there is a relation between the bright spectrum with dark lines emitted by the Sun, and the bright lines emitted by elements in the lab. Kirchhoff described this relation in the form of three 'laws':
- 1. A hot opaque body, such as the ideal black body, or a star, emits a continuous spectrum.
- 2. A hot transparent gas produces an emission line spectrum.
- 3. A cool transparent gas in front of a hot opaque body produces an absorption line spectrum.

# Kirchhoff's laws

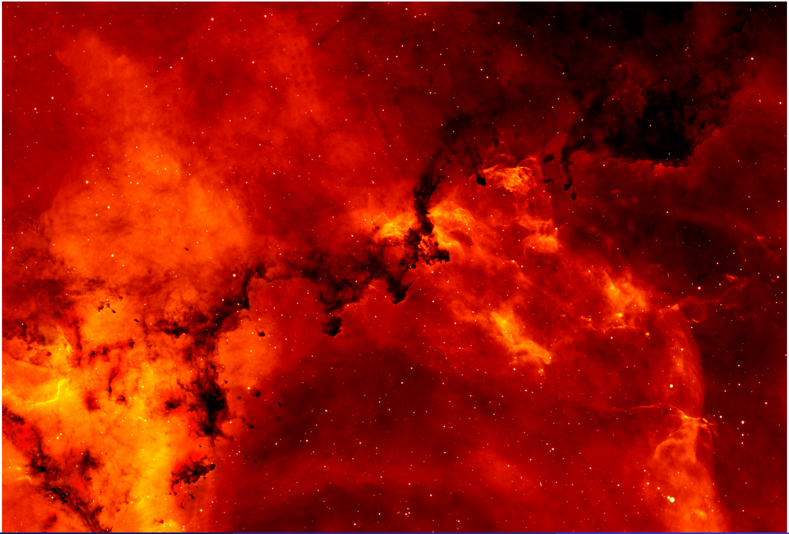
- The Sun's spectrum can then be understood as being produced as light from the hot surface passes through the cooler atmosphere.



# Kirchhoff's laws

- Kirchhoff's laws are the foundation of spectroscopy. The power of spectroscopy is enormous: we can determine the composition of objects that are at enormous distances from Earth.
- One very important observation is that a bright red emission line at 656.3nm is extremely common in the universe.
- This red line is emitted by hydrogen, and hydrogen is the most abundant element in the universe.

# Kirchhoff's laws



# Why different atoms emit different spectral lines

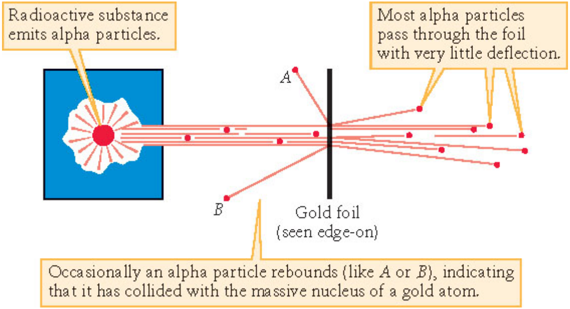
- The fact that different atoms absorb and emit radiation only at particular wavelengths tells us a great deal about extremely distant astronomical objects.
- Much closer to home, it also tells us about the fundamental structure of matter. It cannot be explained by the wave theory of light, and the reasons why matter behaves in this way did not become clear until the 20th century.

# The structure of matter

- Ernest Rutherford made a surprising discovery about the nature of matter, a few years after the discovery of the electron.
- He fired alpha particles (a form of radiation) at a sheet of extremely thin foil, only a few atoms thick. He expected that most of the helium atoms would be deflected a small amount by the electrons in the gold foil.
- This kind of experiment (firing particles at other particles, to investigate the very small scale structure of matter) is still fundamental to atomic research today, but on a vastly bigger scale (eg CERN)

# The structure of matter

- In fact, most of the helium atoms passed through with almost no deflection at all. A very small number were deflected by a large amount.
- This showed that the atoms in the gold had the vast majority of their mass concentrated in a very small volume.



# The structure of matter

- Rutherford said he was as surprised as if he'd fired a cannonball at a piece of tissue paper and seen it rebound.
- His result led to the understanding of an atom as consisting of a very small and dense nucleus, containing almost all of the mass of the atom, surrounded by a shell of electrons.
- If an atom were the size of a football field, its nucleus would be about 1cm across.

# The structure of matter