Lecture

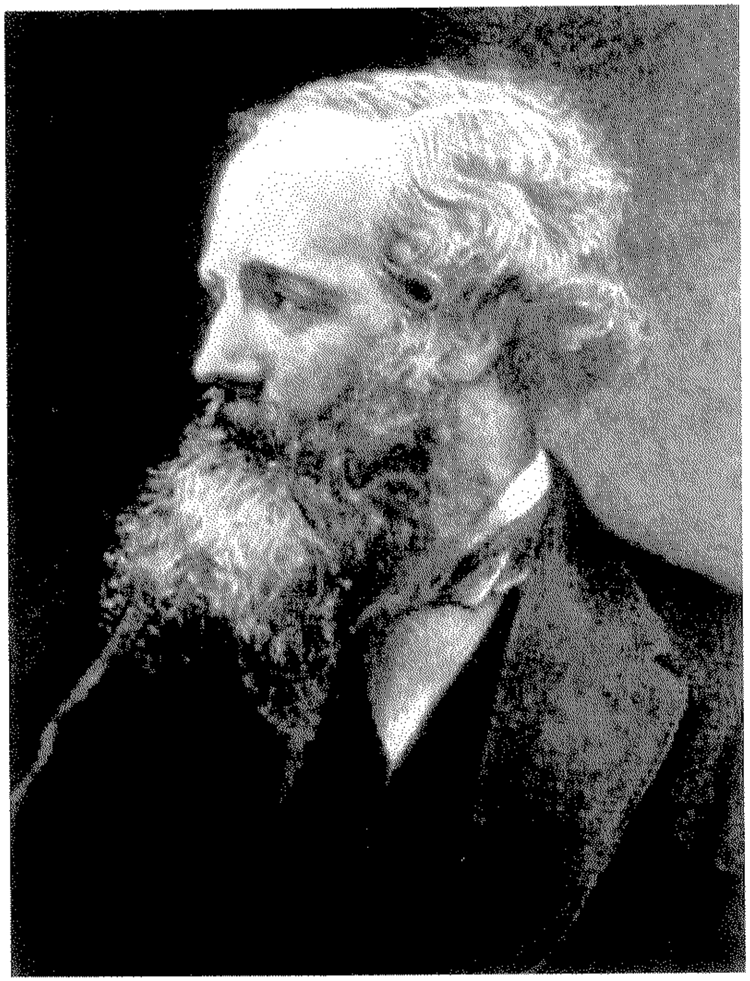
4/21/05

Outline

- Light is Electromagnetic!
- On to the 20th century!
- Spectral Lines
- Thermal Radiation
- The Photon Model of Light

Maxwell's Synthesis

- In 1865, a Scottish physicist named James Clerk Maxwell put together everything that was known about electricity and magnetism in a single coherent synthesis.



Unifying Electricity, Magnetism, and Light: Maxwell's Unified Field Theory

- Maxwell's equations provide the first "Unified Field Theory" – a set of equations that describe two fields (electric and magnetic) and specify the relationship between them.
- These equations turn out to be highly accurate until one gets to distances that are small compared to atomic sizes / energies that are large compared to atomic energies.
- These equations turn out to conflict with Newton's laws with respect how things look to moving observers – and Maxwell's equations turn out to be right and Newton's wrong. This requires us to modify Newton's laws when speeds get near to c and led to Einstein's relativity.

Maxwell's Rainbow

- Since EM radiation is produced by and produces oscillating charges, it's not surprising that different frequencies of oscillation interact with matter differently.
- Matter has its own natural oscillation frequencies so it produces certain frequencies of EM radiation when it's set into oscillation and it reacts with different frequencies of EM radiation in different ways.
- In general, EM radiation is a mix of different frequencies. The frequencies it contains is called its *spectrum*.

The Electromagnetic Spectrum

Name	*Frequency (Hz)*	*Wavelength (m)*
Long	$> 10^4$	$>10^4$
Radio	10^4-10^{11}	10^4-10^{-3}
Infrared	10^{11}-10^{14}	10^{-3}-10^{-6}
Visible	10^{14}-10^{15}	300-600 nm
Ultraviolet	10^{15}-10^{17}	10^{-7}-10^{-9}
X rays	10^{18}-10^{21}	10^{-10}-10^{-13}
Gamma rays	$>10^{22}$	$<10^{-13}$

On to the 20th Century!

- The picture of matter as made up of atoms and light as being an electromagnetic wave looked, at the end of the 19th century, as being a complete and accurate picture of the world.
- When we began to consider the interaction of light and matter, things began to change.

How does matter emit light?

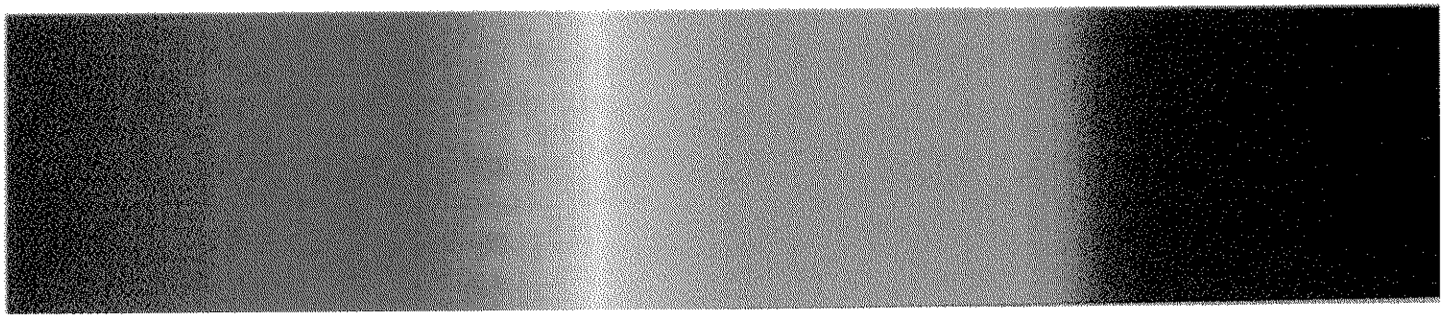
- We know that when we add enough energy to matter it can give off light.
- One way is to get it hot enough.
- Another way is to add energy through an electric spark (e.g., a fluorescent tube) or electron beam (e.g., x-ray tubes)

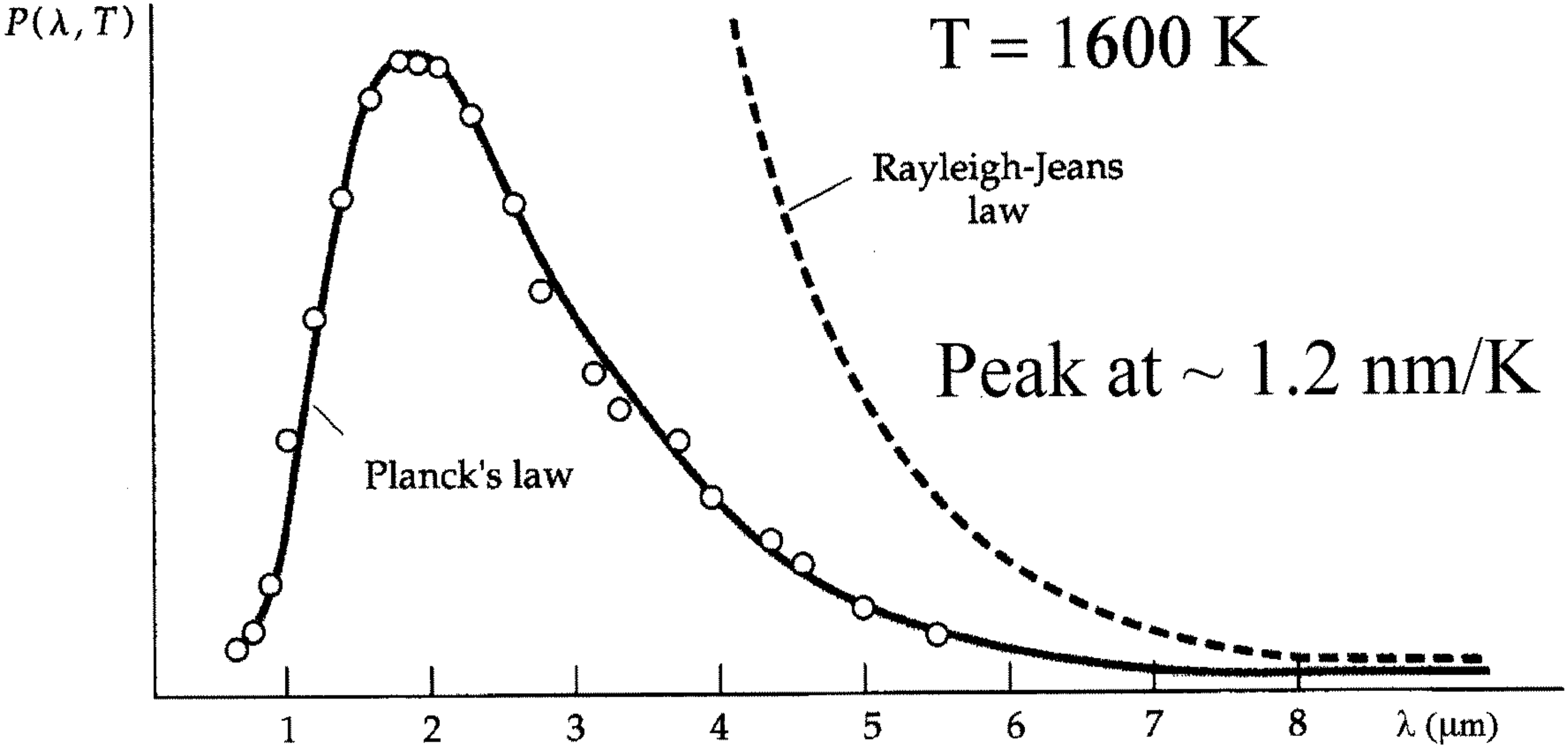
Thermal radiation

- In order to concentrate on the properties of EM radiation associated with a given temperature, 19th century physicists constructed perfect radiators and absorbers (= “black-body” or “cavity” radiation).
- The idea was to have a box made of some material at a temperature T with a small hole in it.
- The EM radiation inside the box would be at equilibrium with the matter (i.e., at a temperature T).
- Any radiation hitting the hole would get out.
- The emission from the hole would tell you the character of the EM radiation inside.

Results

- The distribution of wavelengths present in the EM radiation emitted from a black-body is independent of the material the box is made of (as expected).
- The amount of energy as a function of wavelength peaks at some value that decreases as the temperature goes up.
- The energy goes to 0 at high or low wavelengths.
- The distribution of colors give a *continuous spectrum* of light.





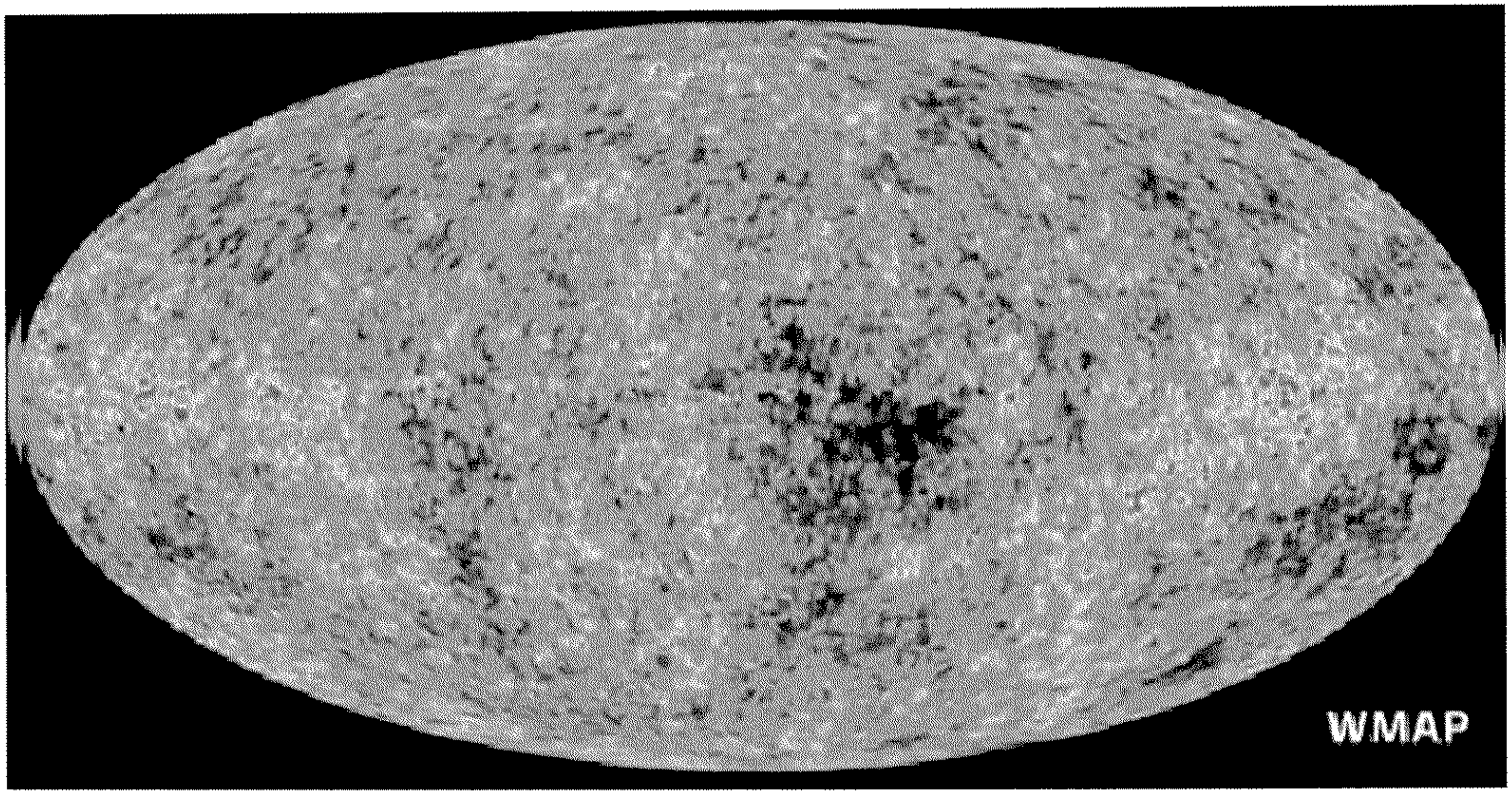
T = 1600 K

Peak at ~ 1.2 nm/K

Modern Implications

- The average temperature of the universe has been measured by measuring the EM radiation in space. It fits the Planck curve extremely well for T ~ 3 K.
- Since the universe is not now in thermal equilibrium, the existence of this radiation suggests that at some time long ago, it was, and that the EM radiation in the universe was in equilibrium with the matter.
- This fits very well with (and was predicted by) the big-bang model of the evolution of the universe.
- Recently, extensive experiments (COBE / BOOMERANG) have measured the very small (μK) temperature fluctuations in the temperature of this radiation. These fluctuations have been predicted by models of the early universe. Their measurement will help us understand which models are the best.

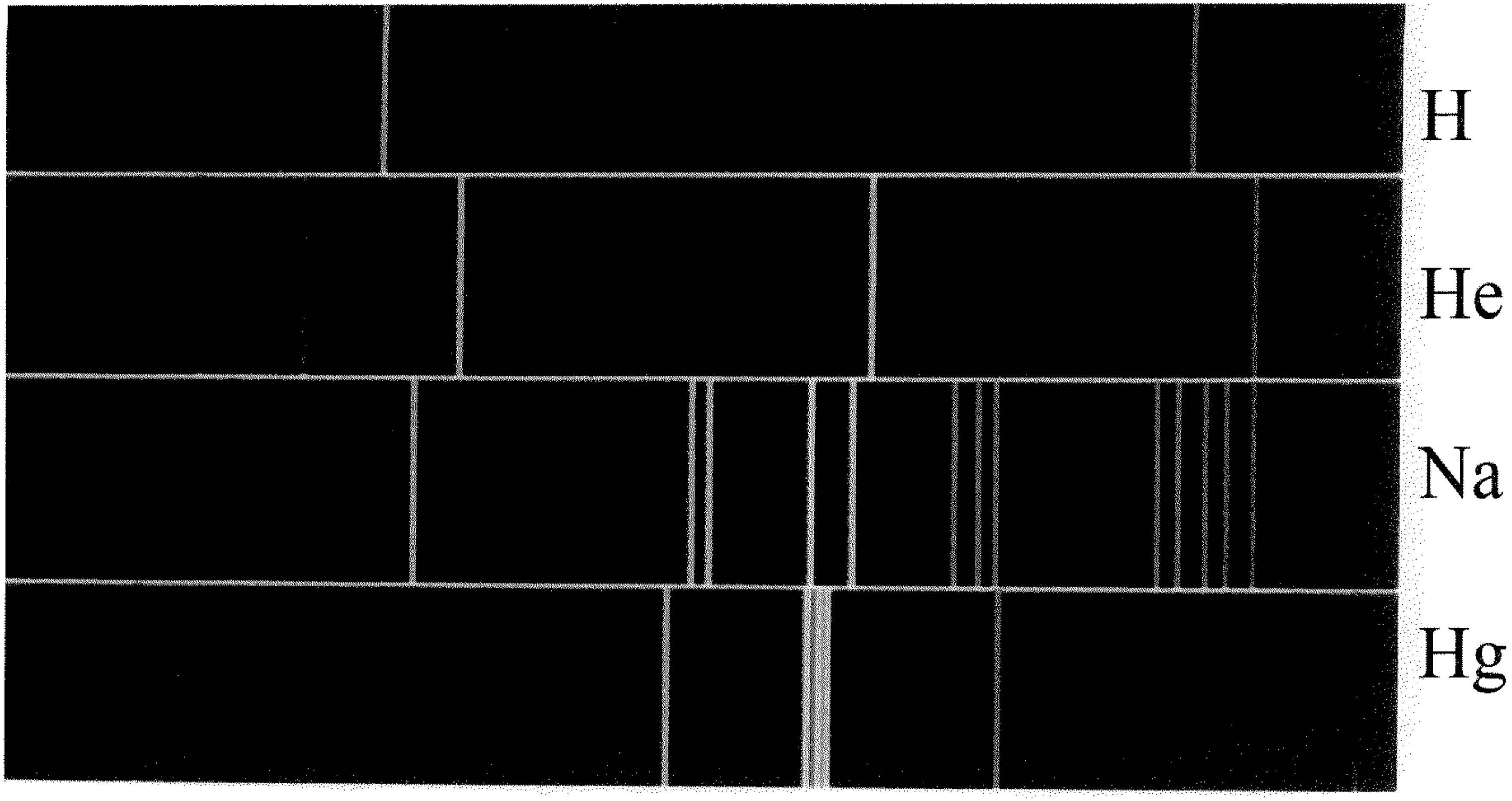
The Cosmic Microwave Background
(Taking the temperature of the sky)



Line Spectra

- Heating matter isn’t the only way to get light.
- When energy is added to gases of pure atoms or molecules by a spark, they give off light, but not a continuous spectrum.
- They emit light of a number of specific colors — *line spectra*.
- The positions of the lines are characteristic of the particular atoms or molecules.

Line Spectra



Implications

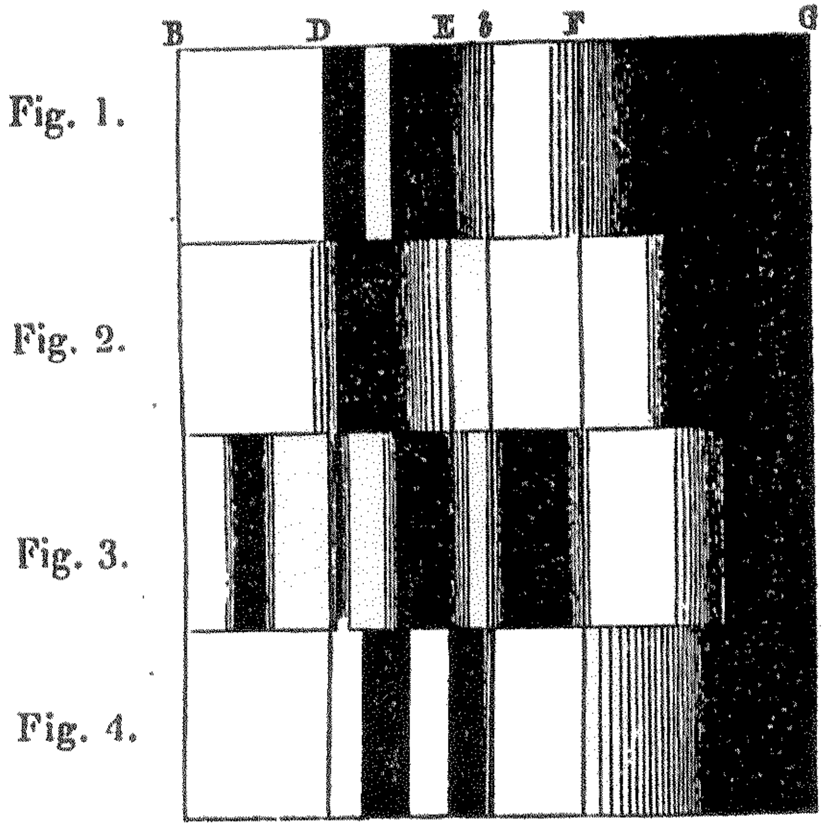
- This property of matter lets us do some rather remarkable things:
  - chemical flame tests
  - identify the composition of the sun and distant stars
  - identify the composition of a plume of smoke emitted from a smokestack
  - determine the relative composition of atoms in a rock and therefore determine its source

Absorption Spectra

- If a continuous spectrum is put through a gas of a particular kind of atom or molecule, the atom’s spectral line appear as dark lines — absorption lines — over the continuous spectrum.
- It appears that the atoms not only can emit light of a particular frequency, they can absorb light of that frequency as well.

Biological Applications

- Since different molecules have different spectra, chemical reactions can be probed by looking at spectra.
- Stokes first determined that hemoglobin was responsible for carrying oxygen in the blood by doing a spectral analysis. (1864)



A Possible Explanation

- In 1899, Max Planck pointed out a way out.
- The classical approach said
  in thermal equilibrium, every place you could
  put energy got 1/2 $k_B T$ of energy.
  That seems not to work at high frequency.
- Planck suggested that the oscillators in the walls
  of the cavity could only absorb energy
  of angular frequency ω in chunks $\hbar\omega$
  where $\hbar$ was a new constant.
  - This cut off the curve at high ω (small λ)
  - Choosing $\hbar$ to fit the data gave an excellent fit to the observed curve. ($\hbar \sim 10^{-34}$ J-s)

The Photon Model of Light

- Einstein reinterpreted Planck's results and suggested that the same result could be found if light itself behaved as if its energy came in discrete packets.
- The energy of a light beam would be determined by a combination of 2 characteristics:
  - the energy per packet
  - the density of the packets (number / unit volume)

Einstein's Photon Equations

- Einstein (1905) suggested that photons carry both energy and momentum according to the equations:

$$E = \hbar\omega \qquad\qquad p = \hbar k$$

$$(\text{Recall } \omega = \frac{2\pi}{T} = 2\pi f \quad k = \frac{2\pi}{\lambda})$$

- This equations are somewhat peculiar. We tend to think of the left side of the equations as particle properties and the right side as wave properties.
- Einstein was the first to suggest that some objects in the world have both wave and particle properties.