The Spectrum and the Stars

Bill Smith
2019

The Power of the Spectrum...

The stars are only accessible to us by a distant visual exploration. This inevitable restriction [....] forbids speculations relative to their chemical or even physical natures.

August Comte 1844.

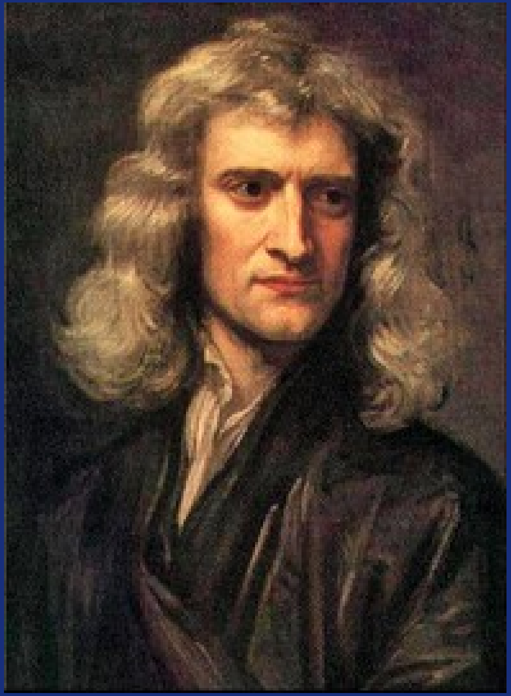
The Power of the Spectrum...

French philosopher August Comte argued that the distances to the stars made it impossible ever to learn about their true nature. It seemed to him that this presented a clear proof that the scientific approach was limited.

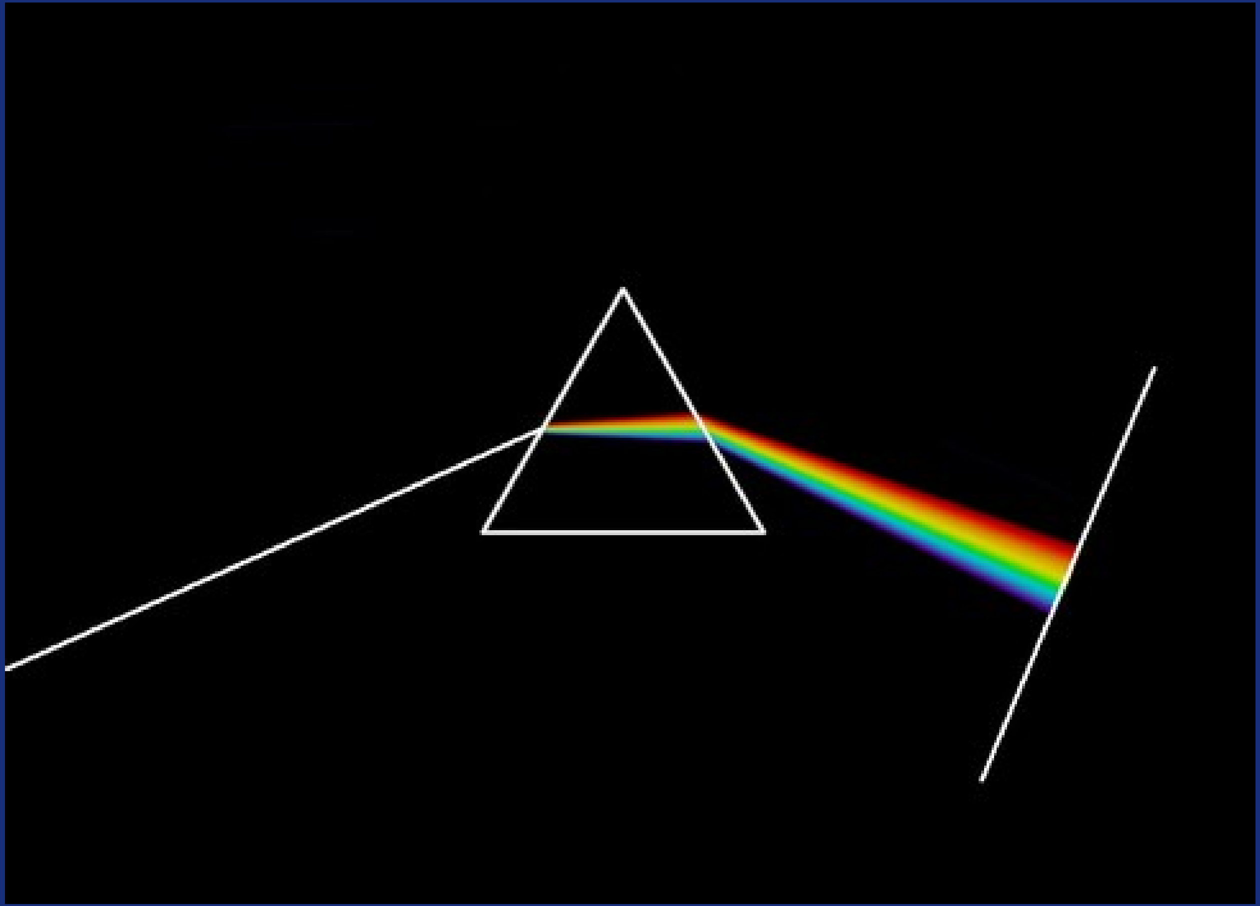
However, he did not know that the light from the stars was full of useful information, from which a great deal of insight onto the nature of stars, and indeed the universe, could be obtained.

Spectroscopy was to play the major role in this quest.

The Spectrum



Isaac Newton 1643-1727



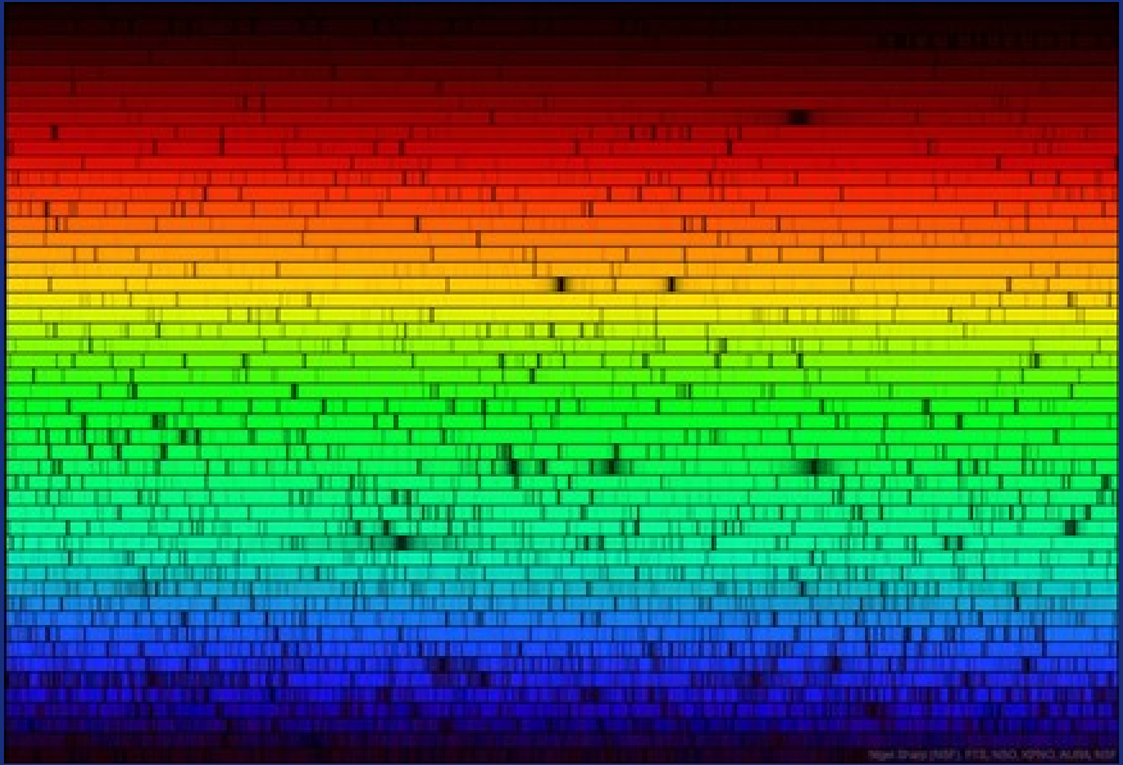
The Spectrum

Isaac Newton famously explored the properties of the spectrum at a young age. He was the first person to realise that the colour spectrum obtained with a glass prism revealed something fundamental about the nature of light. Light was not uniformly white, it was a mixture of the colours, and he devised ingenious experiments to prove this.

Since it was light that carried the attribute of colour, this meant the apparent colour of an object was a result of how light interacted with its surface. In this observation lies the origin of spectroscopy: light that has interacted with matter thereafter carries information about the matter in in the spectrum of its colour spectrum.

The Solar Spectrum

Joseph von Fraunhofer 1787-1826
Maker of glass and optical instruments.
Inventor of the Spectroscope c. 1814.



Fraunhofer lines.

The Solar Spectrum

Joseph von Fraunhofer was a glass manufacturer who specialised in optical glass. In the course of his research he developed optical instruments to investigate the quality of his glass. One of which was the spectroscope, which was great advance over Newton’s simple prism. Pointing this at various sources of light he began to notice that dark lines appeared in many of their spectra. He inevitably directed it at the sun and duly discovered a great number of lines in its spectrum.

These lines are now called Fraunhofer’s lines. From there he went on to look at the spectra of bright stars and found similar lines. Though he did not know what these lines represented, this was the beginning of stellar spectroscopy.

The Colours of Stars

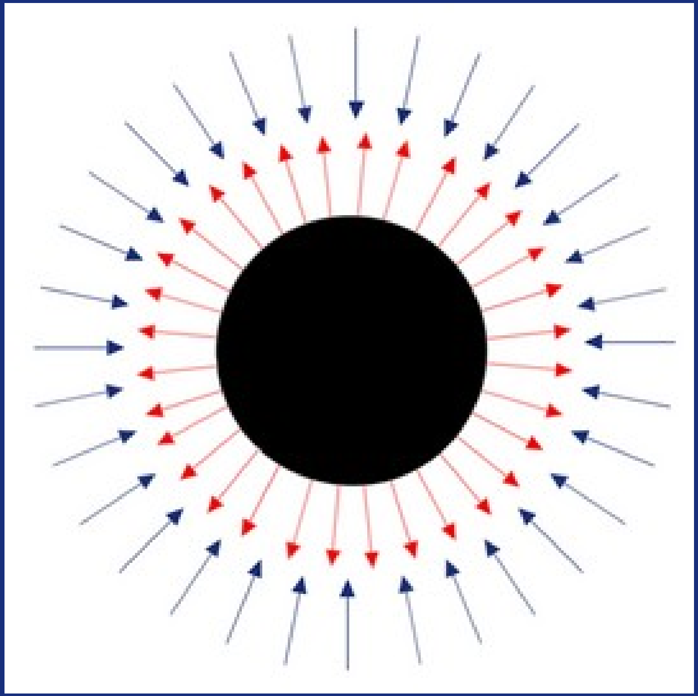
(Astronomy Picture of the Day)

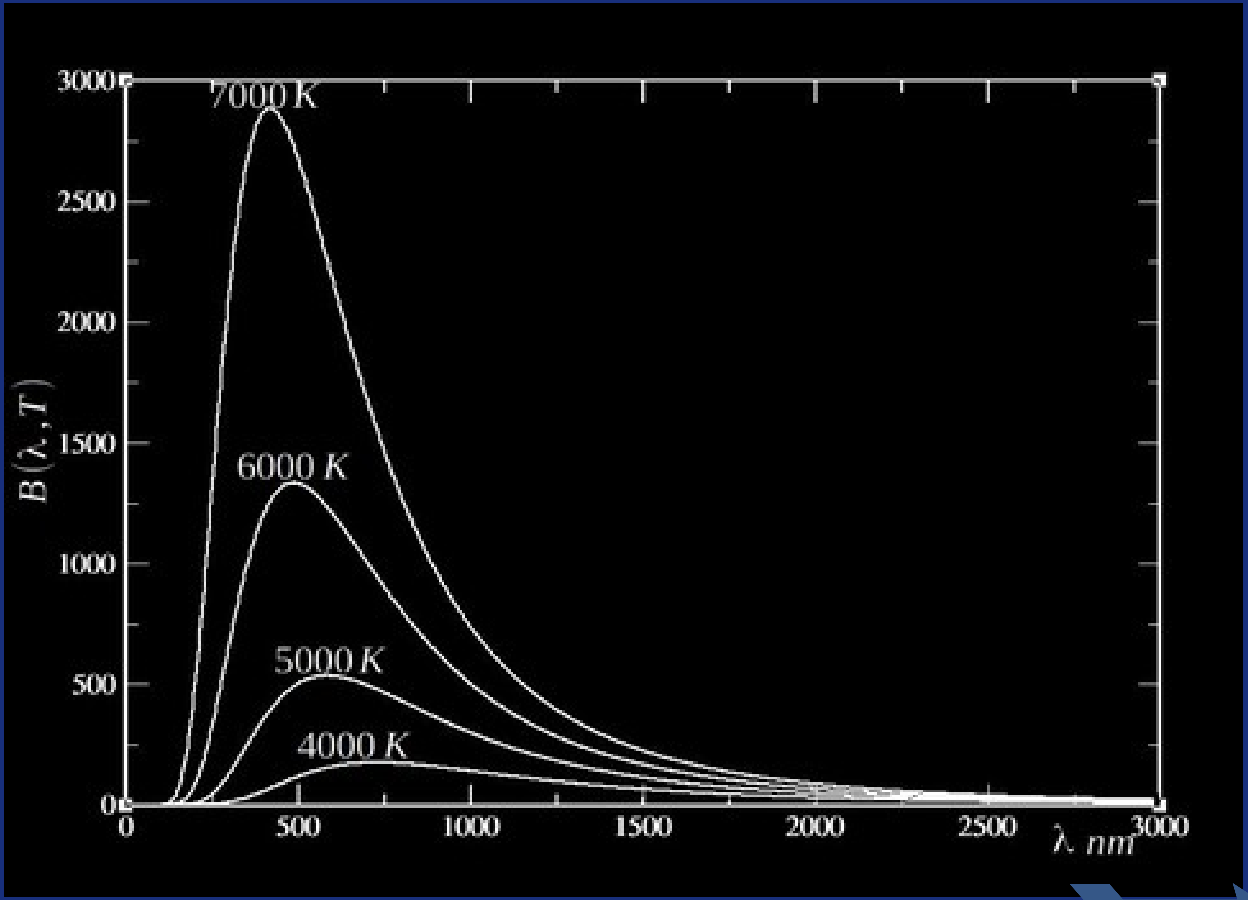
The Colours of Stars

It is well known that stars are coloured. This picture of bright stars that appeared on the Astronomy Picture of the Day website demonstrates this fact beautifully. But what is the origin of these colours?

The colours of the stars (and the lines in their spectra) defied explanation until the emergence of quantum mechanics in the early 20th Century. In the case of the star colours, the explanation lies in the so called the Black Body Spectrum.

The Black Body Spectrum





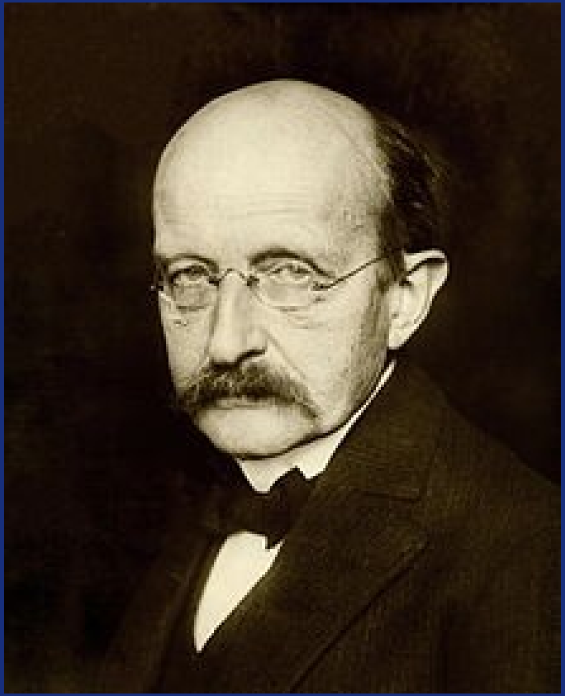
The Black Body Spectrum

A ‘Black Body’ is an idealized body so black it absorbs all light that falls upon it. Such a body, according to the laws of thermodynamics, must also radiate light, otherwise it would keep absorbing light energy until its temperature exceeds that of its surroundings, which thermodynamics forbids.

Experiments with model black bodies (called hohlraums) were used to determine the spectrum a black body emits at different temperatures (see figure). In all cases the spectrum rises from zero to a peak intensity at short wavelength and falls towards zero at longer wavelengths. The peak intensity increases with temperature and shifts towards shorter wavelengths.

There was no theory based on classical mechanics that could describe this behaviour.

The Black Body Radiation Formula



Max Planck 1858-1947

- Planck postulated that the energy of the atoms in the black body was quantised:

$$E = nh\nu \quad \Delta E = h\nu$$

- This led to Planck's formula for Black Body Radiation (1901):

$$B(\lambda, T) = \frac{8\pi hc}{\lambda^5 \left(e^{hc/kT\lambda} - 1\right)}$$

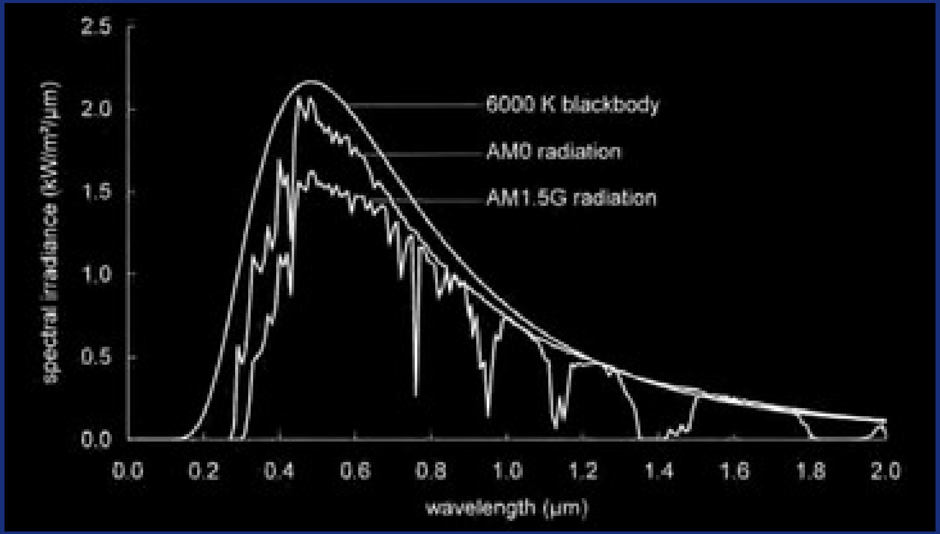
Black Body Radiation Formula

In 1901 the physicist Max Planck produced a formula describing the black body spectrum exactly.

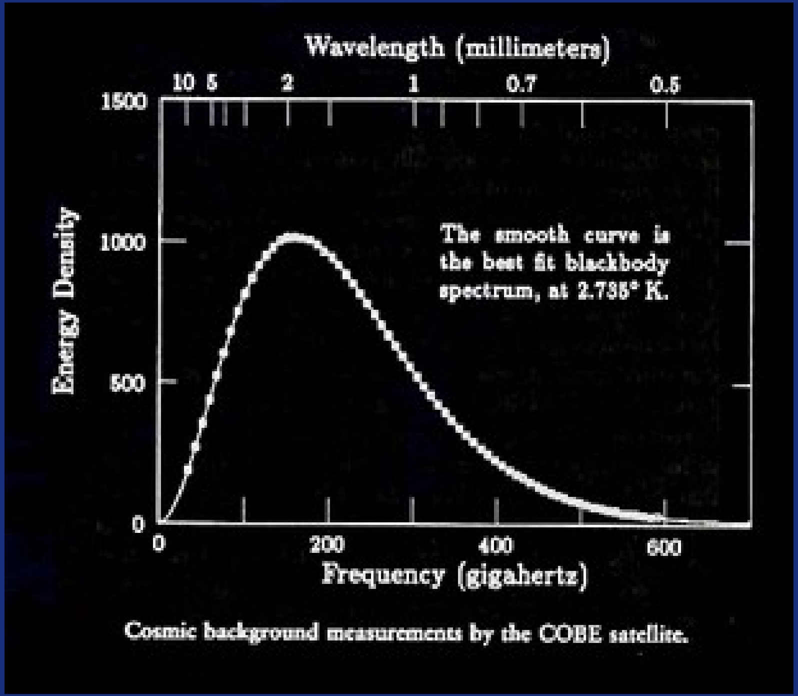
To obtain this however, Planck was forced to assume that the energy of the atoms in a black body was restricted to discrete levels. The emission of radiation (light) occurred when atoms dropped from higher to lower energy levels and released a photon of light with a particular wavelength. The absorption of radiation was the exact opposite of this process. His radiation formula, derived from this model, fitted the data perfectly.

Beyond providing a fit to the data, there was no justification for his theory in classical mechanics. The era of quantum mechanics had begun.

Black Bodies?



The Sun



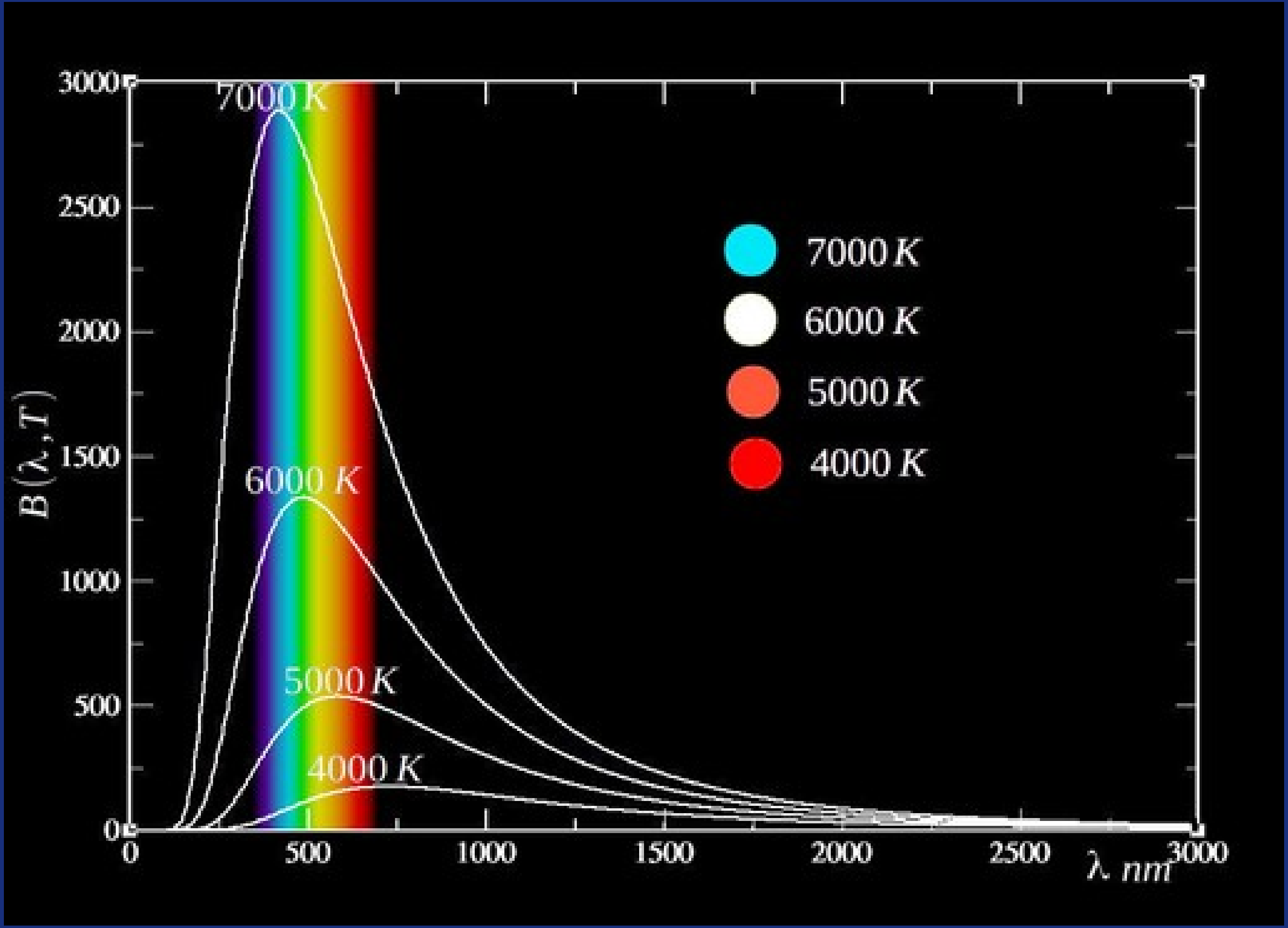
The Cosmic Microwave Background

Black Bodies?

The black body spectrum is adequate to explain the colours of stars as the figure left shows (in this case for the sun). Though the actual solar spectrum is not an exact fit to that of a black body, it clearly follows the same pattern. The deviations are readily accounted for by radiation absorption in the outer atmosphere of the sun and the atmosphere of the earth.

By comparison the spectrum of the cosmic microwave background however, shown right, is a very accurate fit to a black body. Obtained from an orbiting satellite it shows that in space, there is little absorption by the intervening cosmos.

‘Black Body’ Stars



‘Black Body’ Stars

How the black body radiation formula accounts for the colours of stars is shown in this diagram, where it can be seen that, for stars at temperature 7000K the black body spectrum peaks in the blue part of the visible spectrum (shown as the vertical band of colours). These stars therefore appear as blue.

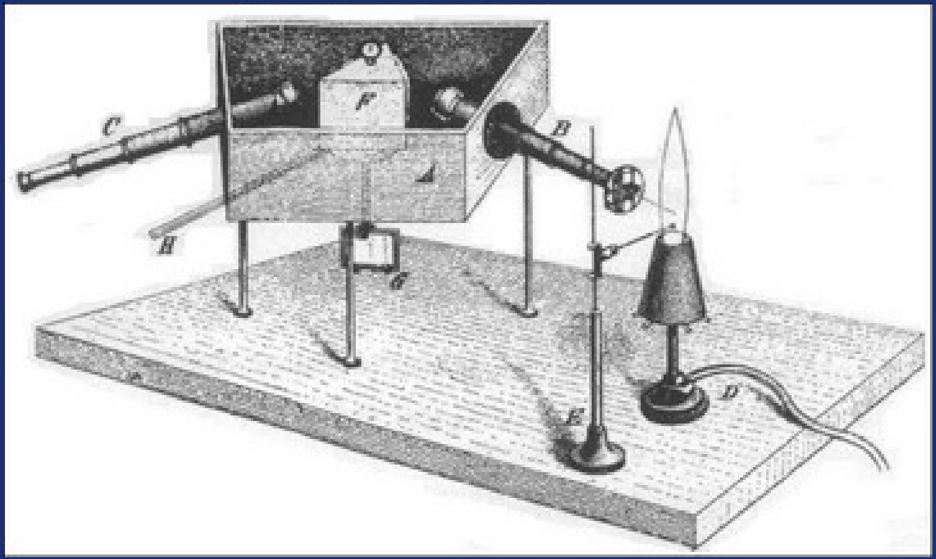
For stars at 6000K, the spectrum peaks in the middle if the visible spectrum and therefore samples all the known colours. The stars thus look white, indeed just as Newton would have predicted.

The spectrum of stars at 5000K peaks in the red-yellow region of the visible range, which gives the stars an orange colour.

The stars at 4000K have a spectrum peak in the red part of the visible range. These stars appear red as a result.

The Chemical Spectrum

Robert Bunsen 1811-99 &
Gustav Kirchhoff 1824-87



Studies of Flame Spectra 1859

Discovery of Caesium (1861) and Rubidium (1862)

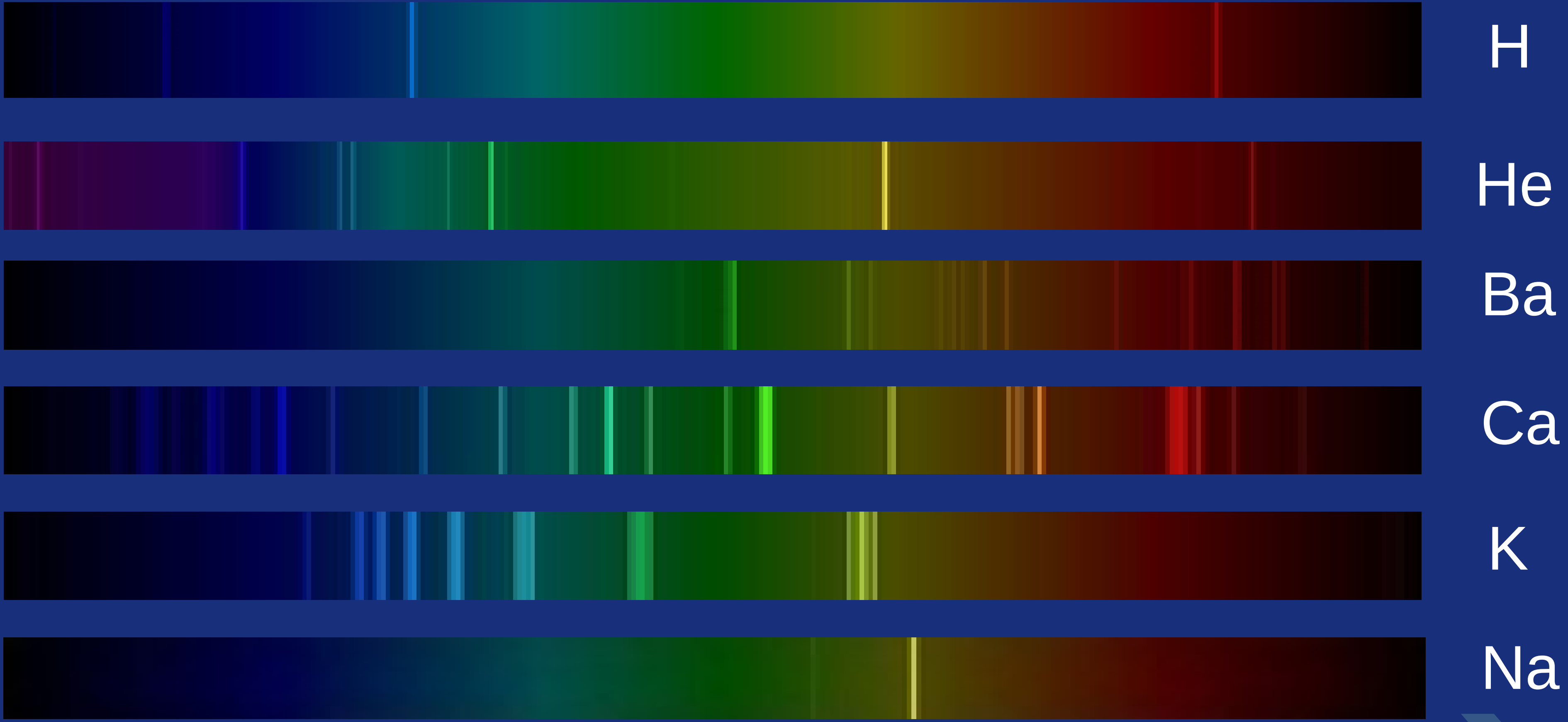
The Chemical Spectrum

The relationship between the spectral lines and the chemical composition of matter was established in a productive collaboration between physicist Gustav Kirchhoff and chemist Robert Bunsen.

Bunsen knew that specific metallic elements gave specific colours to the flames of his famous burner. But of more than one metal was present, determining the metals concerned was difficult. Kirchhoff suggested using a spectroscope and identifying each metal present by it line pattern.

This idea worked so well, they were able to identify many elements in flames of all kinds, including burning buildings! They also discovered new elements Caesium and Rubidium. Soon they stared looking at the stars and became the first people to identify chemical elements in the stars.

Example Bright Line Spectra



Example Bright Line Spectra

Bunsen and Kirchhoff were initially concerned with bright line spectroscopy of the kind shown here. They knew the spectra were unique to specific elements and were able to show that dark line spectra, such as Fraunhofer’s solar spctrum, appeared at the same wavelengths as the lines of bright spectra.

Dark spectral lines are due to light absorption, while light lines are due to light emission. Sometimes both types of line could appear in the same spectrum.

Kirchhoff, went on to devise rules explaining when each kind of line would appear.

Kirchhoff’s Laws of Spectroscopy

- Hot solids, liquids and high density gases produce *continuous* spectra.
- Hot diffuse gases produce *bright line* spectra.
- A continuous spectrum viewed through a cool dense gas produces a *dark line* spectrum.

[Bright and dark lines of the elements occur in the same positions of the spectrum.]

The Sun’s Bright Line Spectrum

Astronomy Picture of the Year 2019

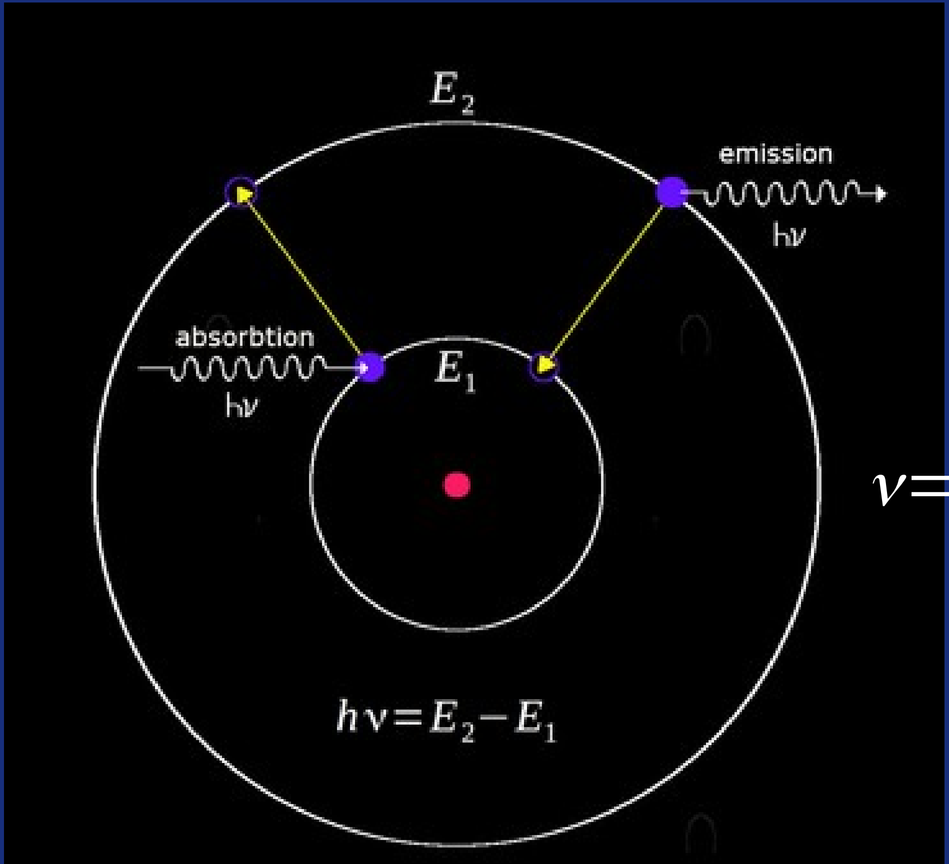
The Sun’s Bright Line Spectrum

This picture is from the Astronomy Picture of the Year 2019. It is a photograph of a total solar eclipse taken through a diffraction grating. As can be seen, the diffraction grating has separated out the colours of the light at the edge of the sun, showing several bright lines.

These lines identify the glowing gas as hydrogen, thus proving that hydrogen is indeed present in the sun. The sun’s bright line hydrogen spectrum is normally hard to see. It is remarkable that this has been done in such a simple way.

The Origin of Spectral Lines

Neils Bohr 1885-1962



The Bohr Model 1913

$$\nu=\left(\frac{m_e e^4}{8\,\epsilon_o^2 h^3}\right)\left[\frac{1}{n_1^2}-\frac{1}{n_2^2}\right]$$

The Origin of Spectral Lines

The explanation of spectral lines (at least for the hydrogen atom) was obtained by Niels Bohr in 1913. The explanation was rooted in quantum mechanics. Bohr assumed that the electrons in the atom could only have discrete energy values set by quantum rules. Electrons could only jump to higher energy levels when a photon of light with a specific wavelength and energy supplied the energy for the jump. The absorption of light of this wavelength caused dark lines in the spectrum. Likewise an electron could drop from a higher energy level and emit a photon with a specific energy and wavelength, which would show up in the spectrum as a bright emission line.

The formula shown calculates the frequency of the photon as a function of some fundamental constants and the two energy levels concerned, numbered n_1 and n_2.

This model was too simplistic to explain everything about spectroscopy, but it started a revolution in quantum mechanics leading to a complete account of atomic spectra.

Thermodynamics and the Spectrum

Meghnad Saha 1893-1956

- Saha proposed that atoms exist in many states in stars and their relative abundances affect how prominent their spectra will be.
- [A → A^*_1,A^*_2,… & A^+_1,A^+_2,… & A^{++}_1, A^{++}_2, ….. etc.]
- He developed the Saha ionisation equation that relates a spectrum to the temperature and pressure of its components (1920).
- The theory was later extended by RH Fowler and EA Milne.

$$\frac{n_{i+1}\, n_e}{n_i} = \frac{2\, Z_{i+1}}{Z_i}\left(\frac{2\,\pi m_e k\, T}{h^2}\right)^{3/2} \exp\left(-\chi/kT\right)$$

Thermodynamics and the Spectrum

The state of matter in a star or nebula is a plasma and it consists of many different molecular species, which are usually charged. This abundance of species makes it difficult to analyse the spectrum and determine what species are actually present. In 1920 Meghnad Saha derived a formula that made the analysis possible. This ultimately permitted a deep understanding of the constitution of stars and nebulae and the physical processes that operate within them.

Saha’s equation was later improved upon by R.H. Fowler and E.A. Milne.

Star Temperature

From Planck’s formula:

Wein’s Law: $\lambda_{max} = \frac{hc}{4kT}$

(Not really applicable to stars)

Stephan-Boltzmann Law: $L = \frac{\sigma}{\pi} T^4$

(Bolometric temperature)

Star Temperature

An important issue in the physics of stars is the surface temperature which is, in principle, accessible to observation.

In principle spectroscopy can provide the answer through Saha’s equation, but for a star it is simpler to assume it has a black body spectrum and determine the temperature via Planck’s model. There are two possible approaches:

- Wein’s law relates the peak in the black body spectrum to the temperature. However, a real star is not an ideal black body, which makes this unreliable.

- The Stephan-Boltzmann law directly relates a star’s luminosity to the temperature and this simple method provides what is called the bolometric temperature.

The internal temperature of stars is obtained theoretically, with the surface temperature employed as a boundary condition on the theory.

The Sun and Hydrogen

Cecilia Payne-Gaposchkin 1900-79

- Proposed (1925) that the Sun was mostly hydrogen, based on spectra and the theories of Saha, Fowler and Milne.
- Advised by H.N. Russell to play down this result in her PhD thesis!
- Later vindicated by A. Unsoeld, W. McCrea and ... H.N. Russell!

The Sun and Hydrogen

A number of women have made outstanding contribitions to our understanding of stars. One such woman was Cecilia Payne-Gaposchkin. By applying the methods of Saha, Fowler and Milne to the spectrum of the sun she deduced that the sun was mostly hydrogen – a crucial factor in determining the energy processes within all stars. It was a discovery worthy of a Nobel Prize, but that didn´t happen.

Unfortunately, this deduction was thought incorrect by her contemporaries and she was urged by her supervisor (H.N. Russell) to suppress this discovery in her thesis. It was later verified that she was correct by a number of other researchers (including Russell!), but by then her chance of wider recognition was gone.

Her discovery is now widely and deservedly acknowledged.

Spectra & Stellar Classification

Annie Jump Cannon
1863-1941

- A. Secci (1860’s): I (blue), II (yellow), III (orange), IV (red).
- E.C. Pickering & W.P. Flemming (1890’s): A, B,..,O, based on widths of H lines.
- A.J. Cannon (1901): O, B, A, F, G, K, M scheme with sub-categories A0, … , A9, etc. based on detailed spectrum, temperature ordering - the ‘Harvard’ scheme.
- R, N, S categories added later.
- Scheme adopted by the International Astronomical Union in 1922.

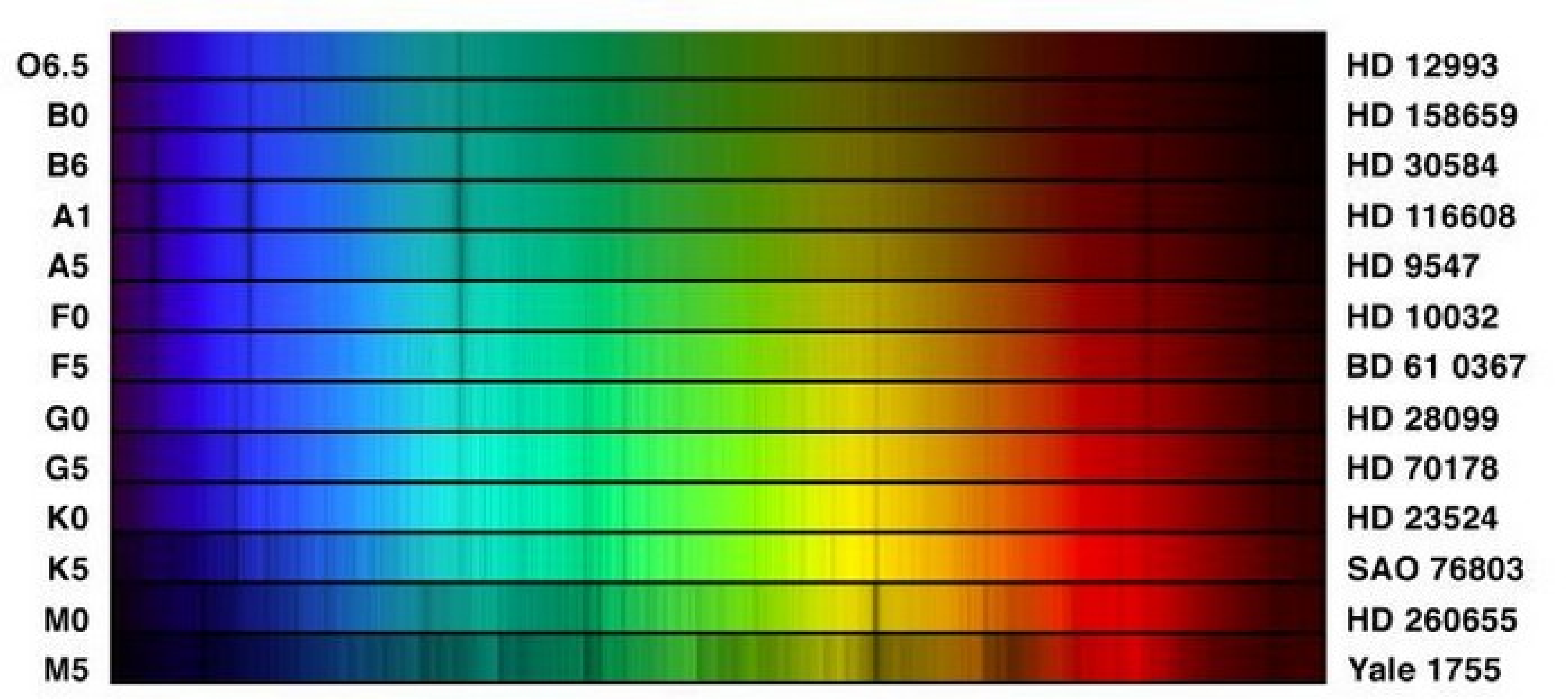
Spectra & Stellar Classification

Other women have made outstanding contributions to astronomy (generally with little acknowledgement at the time). Many of them worked in association with Edward C Pickering at Harvard. This work led to the stellar classification scheme that is in use today, based on the spectrosopic properties of stars: the OBAFGKM scheme.

The first scheme by Angelo Secci was based on the colours of stars, but this was surpassed by the spectroscopic scheme devised by Pickering and Williamina Fleming in the 1890’s. This had alphabetic classes ranging from A to N, based on the strength of hydrogen absortion lines. Later however, Annie Jump Cannon (also at Harvard) revised this scheme. She abandoned some of the classes and arranged the rest into the now familiar order, which is related to temperature, thus tying the classes more closely to the physics of the stars. Later still these primary classes were subdivided into 10 sub-classes numbered from 0 to 9 to give the modern Harvard scheme.

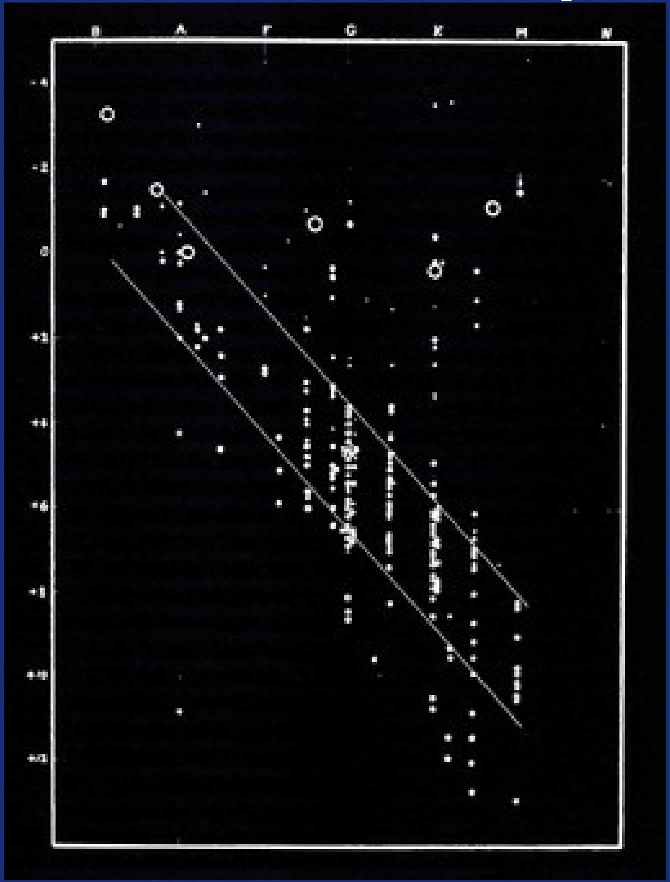
The following slide presents example spectra from each class of the Harvard scheme.The subtle changes between the classes are apparent.

OBAFGKM!

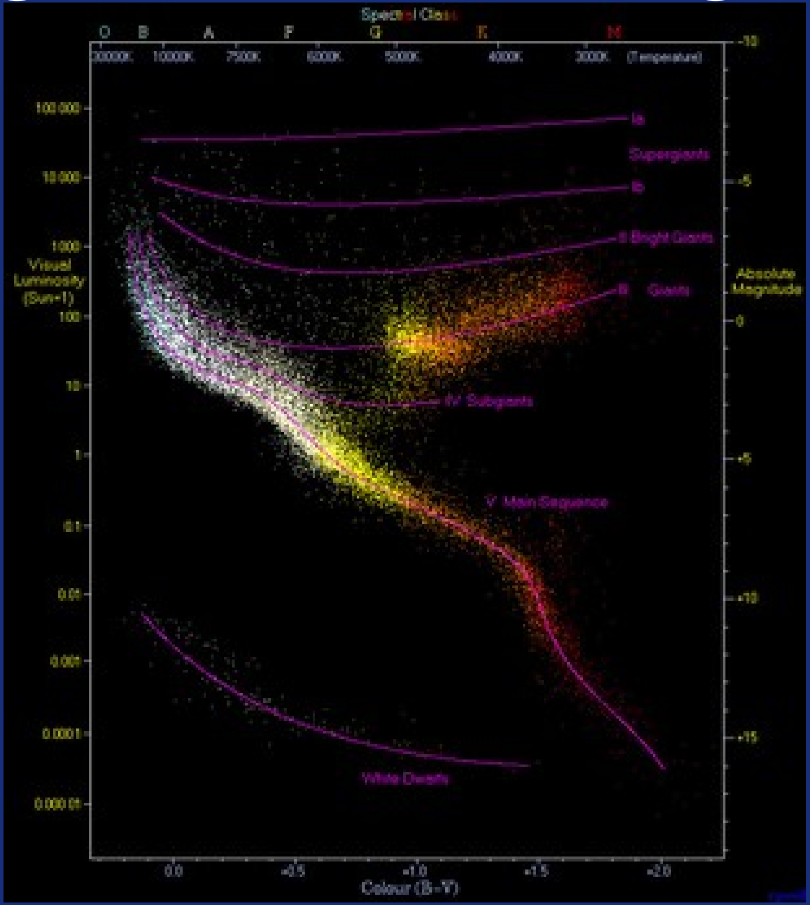


National Optical Astronomy Observatory (Kitt Peak)

The Hertzprung-Russell Diagram



Original (1913)
300 Stars HD Catalogue.



22,000 stars from Hipparcos Catalogue
1,000 Stars from Gliese Catalogue.

www.atlasoftheuniverse.com

The Hertzprung-Russell Diagram

Our understanding of stellar structure and the evolution of stars is greatly informed by the Hertzprung-Russell diagram, which is a plot of stellar luminosity against spectroscopic class for a population of stars. The luminosity is associated with stellar mass and the spectroscopic class with temperature, so the diagram conveniently links observed star properties with stellar physics.

Comparing the H-R diagram for different stellar populations e.g. globular clusters of different ages helps us to understand how stars evolve in time and allows us to date the ages of similar star clusters.

Hertzprung and Russell came up with the H-R scheme independently. They also both recognised the existence of red giant stars, which were not commonly known about, though they were previously identified by Antonia Maury (as Hertzprung acknowledged).

Ejnar Hertzprung

Ejnar Hertzprung 1873-1967

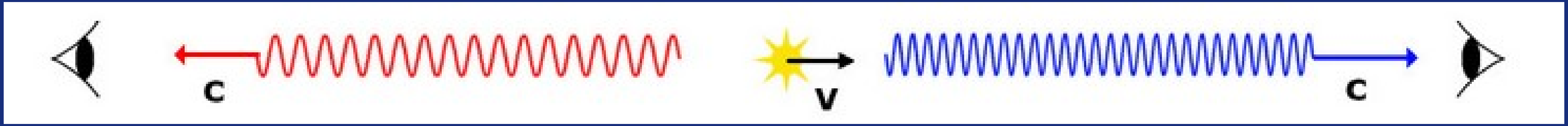
- E. Hertzprung (1905): Categorised stars using both spectral type and luminosity and found a systematic relation between the two.
- Also (re)discovered that some red stars could be extreme variants (as suggested by Antonia Maury).
- Used proper motion to estimate distance.

Henry Norris Russell

Henry Norris Russell
1877-1957

- H.N. Russell (1913): Independently came to the same conclusions as Herzprung and produced the first actual HR Diagram.
- Also recognised the existence of red giant stars.
- Used parallax for distance.

The Doppler Shift



$$z = \frac{\delta\lambda}{\lambda} = \frac{v}{c}$$

Classical form (v<<c).

$$z = \frac{\delta\lambda}{\lambda} = \sqrt{\frac{1+v/c}{1-v/c}} - 1$$

Relativistic form (v-->c).

z > 0 : red shift,
z < 0 : blue shift.

Causes a shift in the positions of spectral lines. How is this useful?

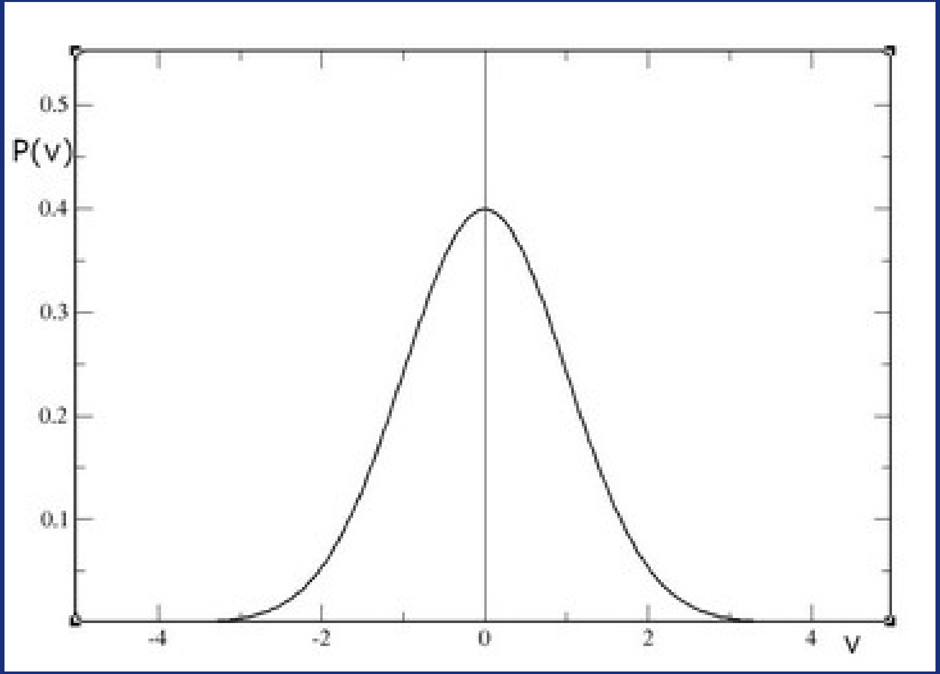
The Doppler Shift

The Doppler shift is an important feature of spectroscopy. A light source that is receding from the observer shows a shift in frequency towards the red end of the spectrum, while an advancing light source shows a shift to the blue.

The shift, measure by the parameter z enables the determination of the speed of an observed object either towards or away from the observer. This gives an insight into the dynamics of the object’s motion.

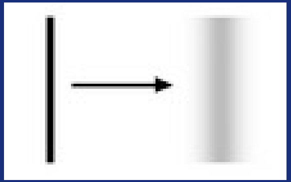
There are several important applications of this in astronomy.

Broadening of Spectral Lines



Maxwell velocity distribution

- A single sharp spectral line is broadened by motion towards and away from the observer:

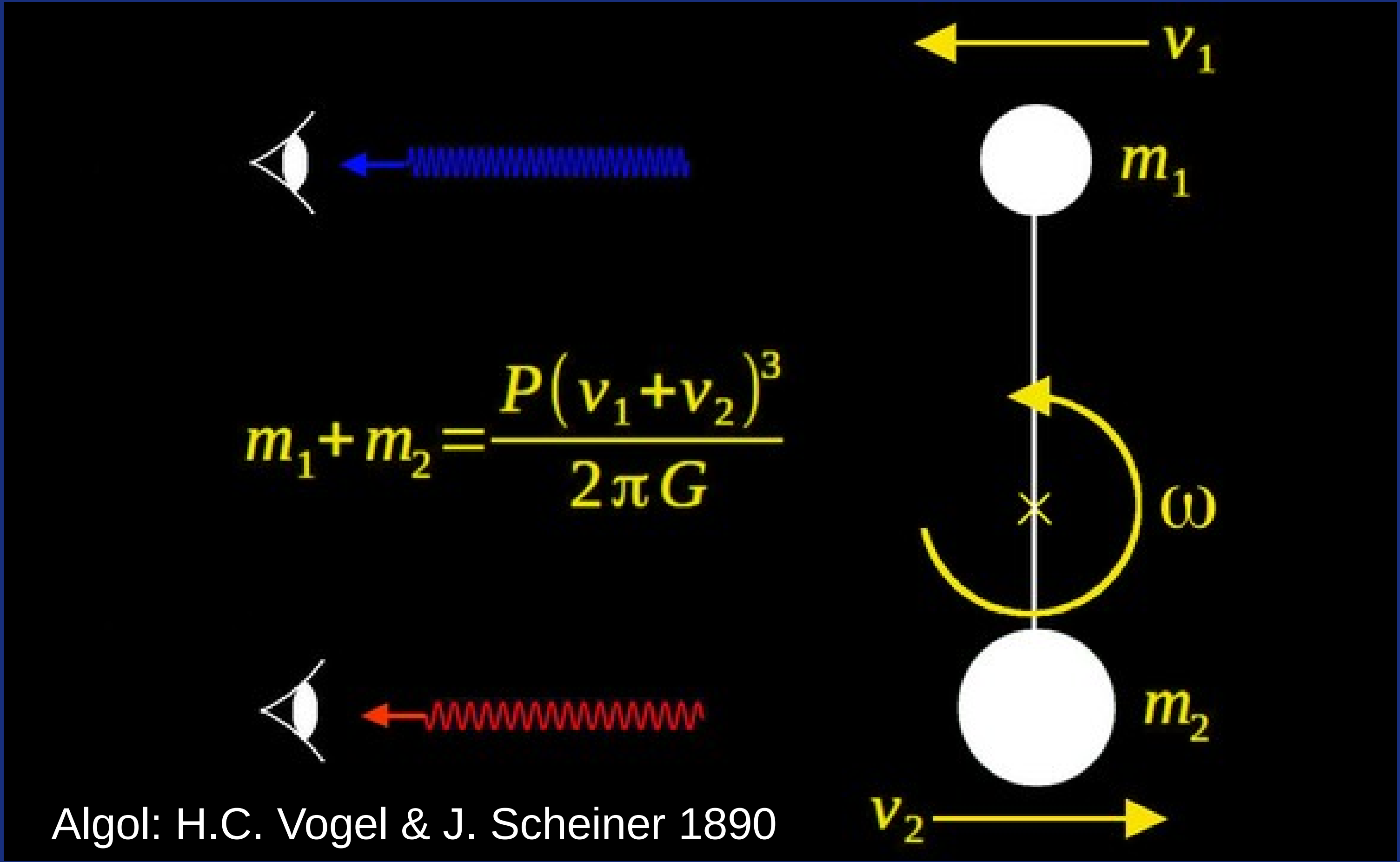


Thermal Broadening.

Broadening of Spectral Lines

The Doppler effect explains why spectral lines appear broader than quantum theory implies. It is because the atoms of objects at a finite temperature have speeds that are distributed about their mean value by an amount determined by the Maxwell-Boltzmann distribution. So some atoms move at either less than or more then the mean value by a small random amount. The differences in the Doppler shifts of these thermalised atoms shows up in the spectrum as a broadening of the lines.

Binary Star Mass



$$m_1+m_2=\frac{P(v_1+v_2)^3}{2\pi G}$$

Algol: H.C. Vogel & J. Scheiner 1890

Binary Star Mass

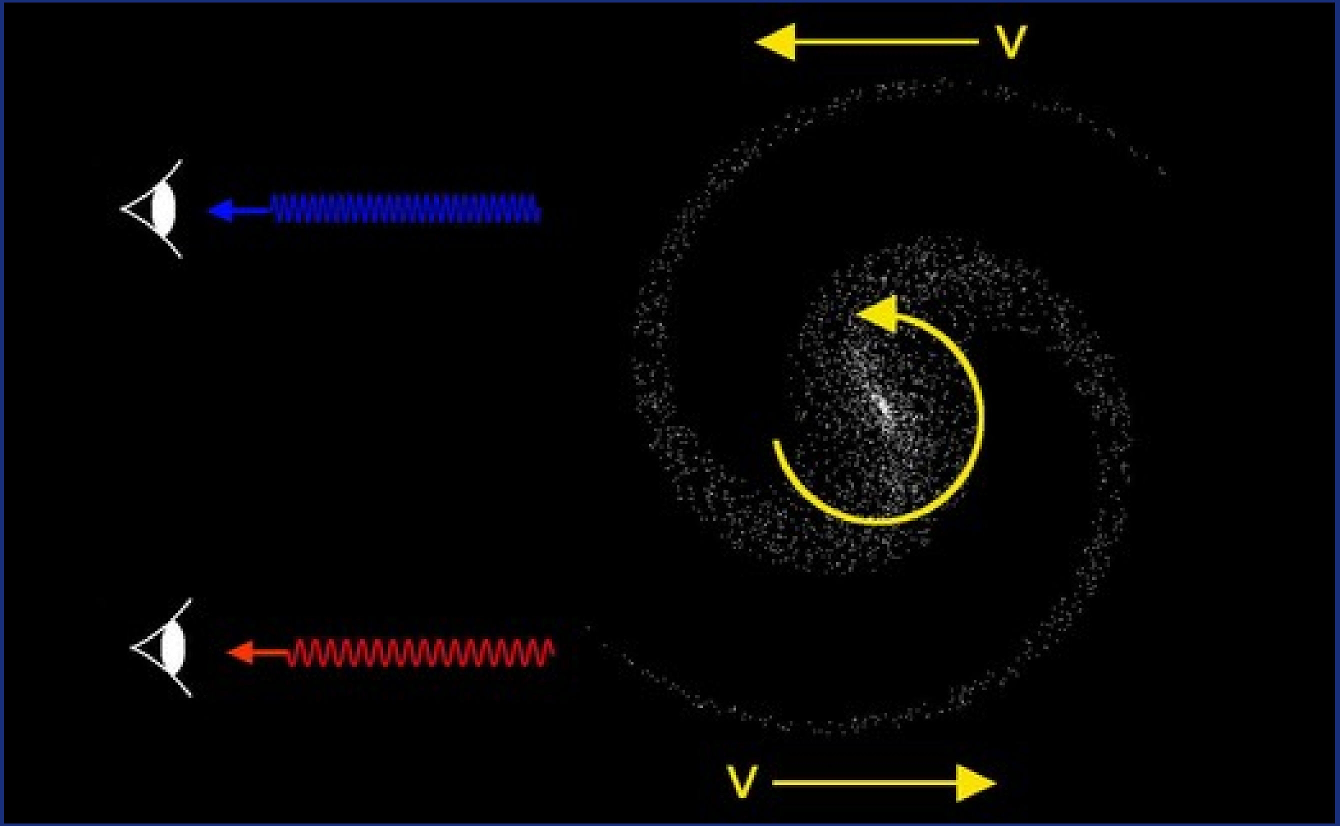
The Doppler shift can also help determine the masses of binary stars that are gravitationally bound to each other. The stars generally move in elliptical orbits which are fixed in a plane in space. If the orbital plane is tilted at a suitable angle with respect to an observer the Doppler shifts of the stars can reveal their relative speeds and so their relative masses.

Furthermore, the period of their orbit can also be found from spectroscopy by obtaining the time dependence of each star's Doppler shift. From this the total mass of the star pair can also be determined using the formula shown.

The Rotation of Galaxies

Vera Rubin
1928 – 2016

‘Dark Matter’



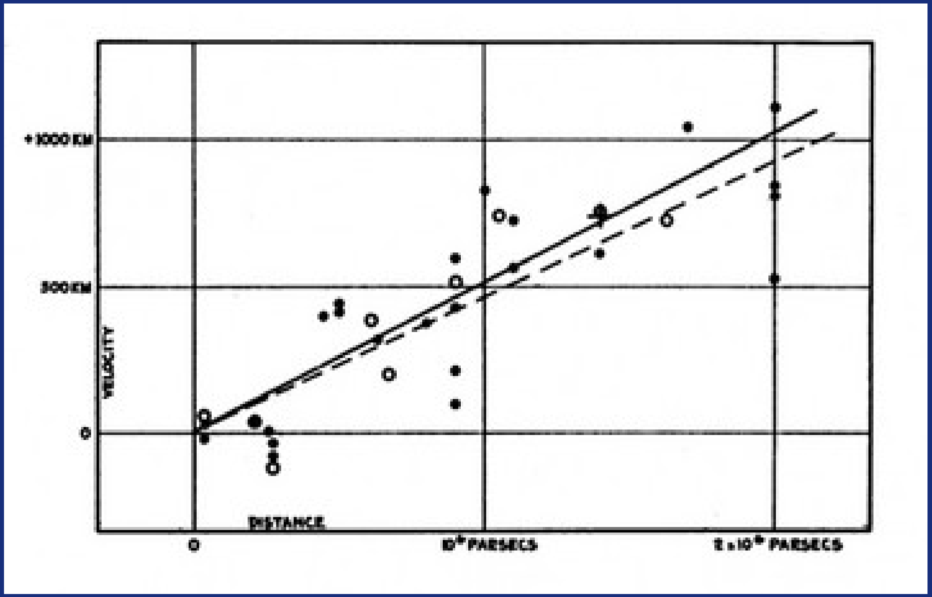
The Rotation of Galaxies

The Doppler effect was instrumental in the discovery of Dark Matter by Vera Rubin, who was able to determine spectroscopically the speeds of stars in different parts of remote galaxies and from this information use gravitational theory to determine the galaxy’s mass. She thus discovered that the deduced mass exceeded the mass of the observable stars and postulated the presence of unobserved dark matter.

Theoretician Fritz Zwicky had also postulated dark matter in 1933, following his study of the Coma Galaxy Cluster, but nobody took notice.

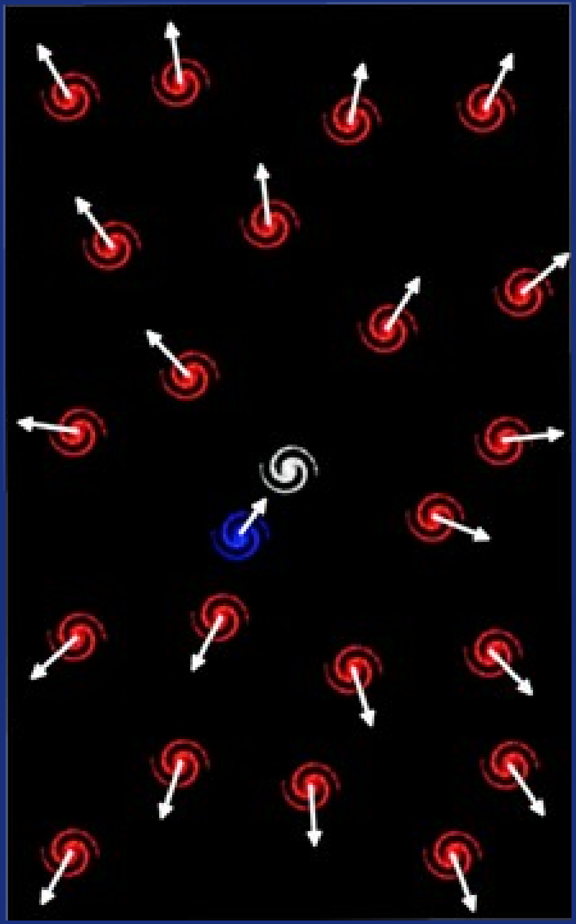
The Expanding Universe

Edwin Powell Hubble
1889-1953



$$v = H_0 d$$

Hubble’s Law



The Expanding Universe

In the early 20th Century, the Doppler shift was applied to the spectroscopic study of galaxies and yielded surprising results.

At Lowell Observatory Vesto Slipher, between 1912 and 1917, discovered through spectroscopy that most galaxies were receding from the Milky Way – evidence that the universe was expanding! By 1929 Edwin Hubble at Mount Wilson Observatory had determined the distances to these galaxies and had shown that their velocities of recession were proportional to their distances. This became known as Hubble’s Law and it proves that the universe is indeed expanding. Remarkably, the theoretician Georges Lemaitre had predicted this from Einstein’s General Relativity theory in 1927.

This is yet another example of the key role spectroscopy has played in our understanding of the universe.

The End