Watt's Up with Emission?

Investigating Blackbody Radiation, the Speed of Light, and Line Spectra

Kaitlyn McHugh
kmm328@pitt.edu
Physical Chemistry Laboratory - CHEM 1430
University of Pittsburgh Chemistry Department

University of Pittsburgh

Outline

Introduction → **Theory & Methods** → **Results** → **Conclusions**

Introduction

- Research purpose
- Significance and applications
- Hypotheses

Theory & Methods

- Principles and mathematics

Results

- Spectral data
- Regression analysis

Conclusions

- Limitations
- Improvements

Purpose: Speed of light, line spectra, and blackbody radiation

Overall goal: To investigate concepts related to light and energy and how these phenomena led to the identification of quantized electronic energy levels in atoms

Speed of Light

- Accurately measure the speed of light
- Determine what factors affect the accuracy of measurements and how to improve

Line Emission Spectra

- Investigate hydrogen and deuterium gases
  - Rydberg constant
  - Ionization energy
  - Mass of deuterium

Blackbody Radiation

- Calculate temperature of blackbody emitters
- Determine which light sources match blackbody emission profiles

Background: Speed of light & line spectra

Speed of light

Fundamental constant used in determining various physical and chemical phenomena

- Various attempts made throughout history to measure it
  - Most values were around 300,000 m/s
- Can be measured by timing how long it takes for light to travel a known distance using mirrors

$$c = 2.9979 \times 10^8 \, m/s$$

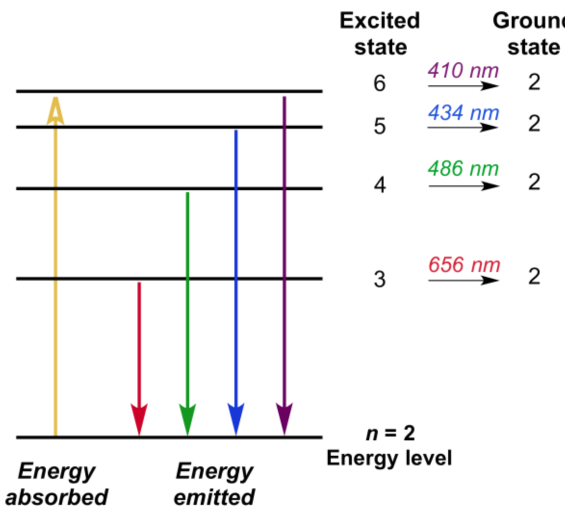
Line spectra

Atoms emit **quantized** amounts of energy due to transitions between electronic energy levels

- Predicted via **Rydberg equation** for hydrogen
  - $\mathfrak{R}$ = Rydberg constant
  - $\boldsymbol{n}$ = principal quantum number
  - $\boldsymbol{\lambda}$ = wavelength

$$\frac{1}{\lambda} = \mathfrak{R}_H \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2}\right)$$

- Characteristic to each element
  - ICP-AES



Energy level structure of hydrogen with various emission lines.

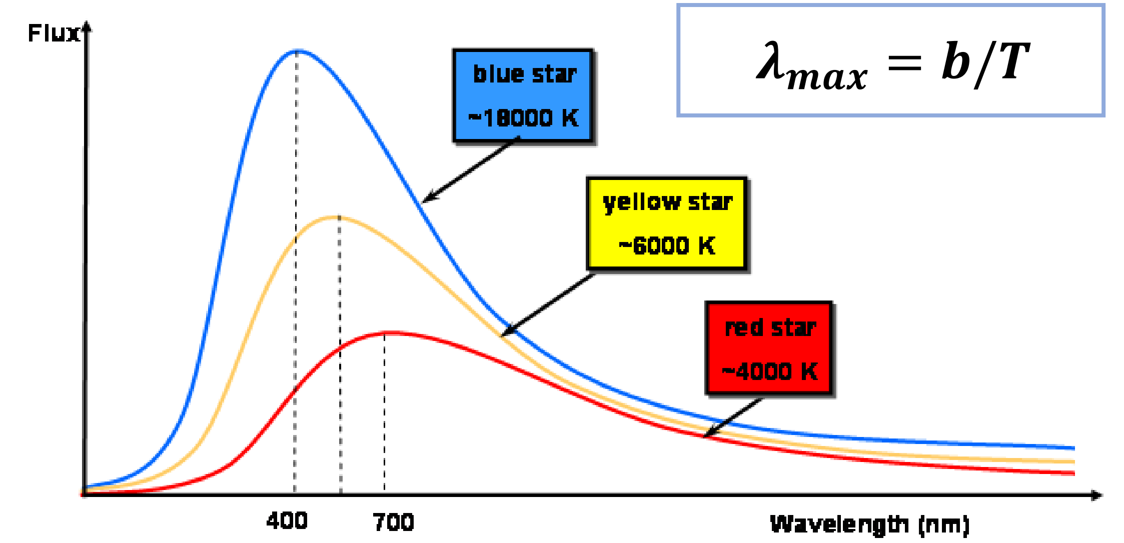
Bohr's Model of Hydrogen. *Khan Academy*.

Background: Blackbody radiation

Blackbody emitters release radiation over a range of frequencies when heated

- Wavelength and intensity are **temperature-dependent**

Wien: increasing temperature of emitting body results in emission at shorter wavelengths



$$\boldsymbol{\lambda_{max} = b/T}$$

Emission spectra of various different colored stars; demonstrates the relationship between temperature of a blackbody and emission wavelength.

Blackbody Radiation. In *Cosmos*. *Swinburne University of Technology*.

Planck: quantization of energy allows for theoretical matching to experimental blackbody emission

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

- Solved the "**UV catastrophe**" of the Rayleigh Jean equation
  - As temperature of an object increases, wavelength of maximum emission decreases – **down to zero**
  - **Not** possible/correct

Hypotheses

1st hypothesis

Blackbody Radiation

The incandescent bulb will demonstrate better correlation to the blackbody emission profile than the LED and fluorescent bulb.

2nd hypothesis

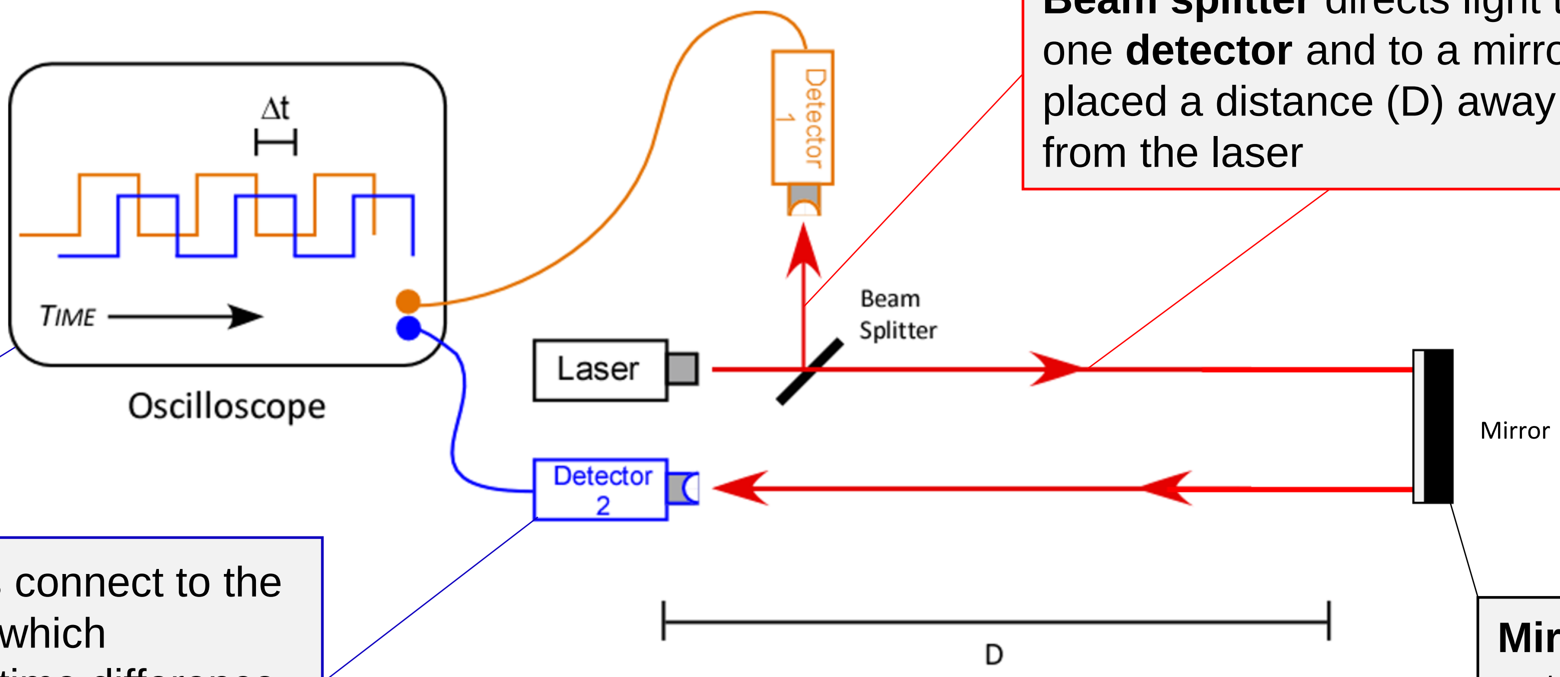
Line Emission Spectra

Intensity of emission lines will be lower for smaller wavelengths, as they represent transitions from high energy states.

Measuring the speed of light

The speed of light was measured using an **oscilloscope**

Beam splitter directs light to one **detector** and to a mirror placed a distance (D) away from the laser



Both detectors connect to the **oscilloscope** which measures the time difference (Δt) between detection of the laser

Mirror reflects incoming light onto the second **detector** placed the same distance (D) away

Measuring the Speed of Light. *Saint Lawrence University*. 2021.

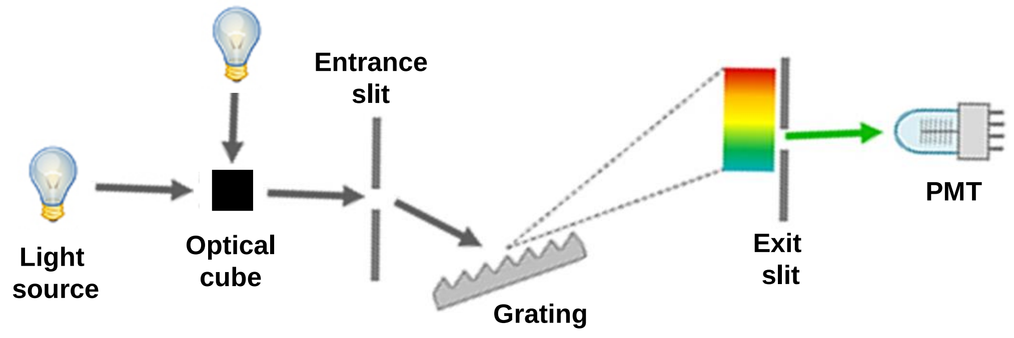
Obtaining line and blackbody emission spectra

Line spectra

Discharge lamps
- Hydrogen and deuterium

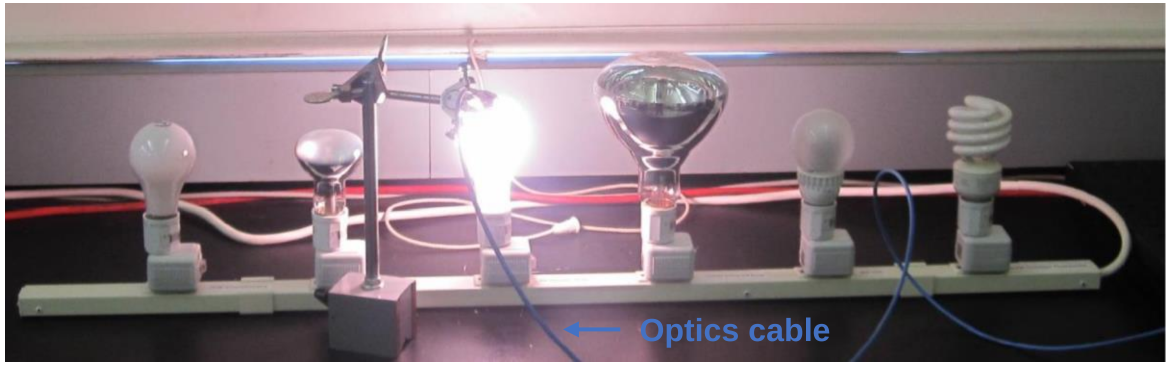
Monochromator
- Used to disperse light emitted by discharge lamps
- Consists of entrance slit, grating, and exit slit
  - Lenses (not shown) and optical cube used to focus light onto entrance slit

Photomultiplier tube (PMT)
- Converts light to an electrical signal
- Allows measurement of low intensity signals



Blackbody spectra

Ocean Optics spectrometer with fiber optics cable
- Emission spectra obtained for **7** light sources
  - 8W LED, fluorescent, GE Reveal, 75W incandescent, 250W IR, 40W halogen, and the Sun



Fiber optics cable was moved between each light source to obtain the emission spectrum.

Adapted from “What is a Spectrometer?” *Edinburgh Instruments*.
Wagner, E. P. Let There Be Light: Investigations of Light, Blackbody Emitters and Line Spectra. 2019.

Speed of Light: Accuracy and how to improve

Speed of light = 3.00 $\times 10^8$ *m/s*

Trial	Path length (m)	Time (s)	Speed of light (m/s)
1	7.37	2.05×10^{-8}	3.59×10^8
2	12.52	3.85×10^{-8}	3.25×10^8
3	15.14	4.70×10^{-8}	3.22×10^8
4	24.79	7.80×10^{-8}	3.18×10^8
5	41.00	1.32×10^{-7}	3.12×10^8

Average speed of light = 3.27 $\times 10^8 \pm$ *1.86* $\times 10^7$ *m/s*

Accuracy

- Percent difference = **9.16%**
- As distance increases, calculated speed becomes more accurate

Possible improvements

- Larger sample size
- Increase distance at which measurements are taken
- Utilize more accurate measuring tools

Blackbody Emitters: Determination of temperature

Wien Temperature

Wien's equation calculates the **temperature** of a blackbody emitter

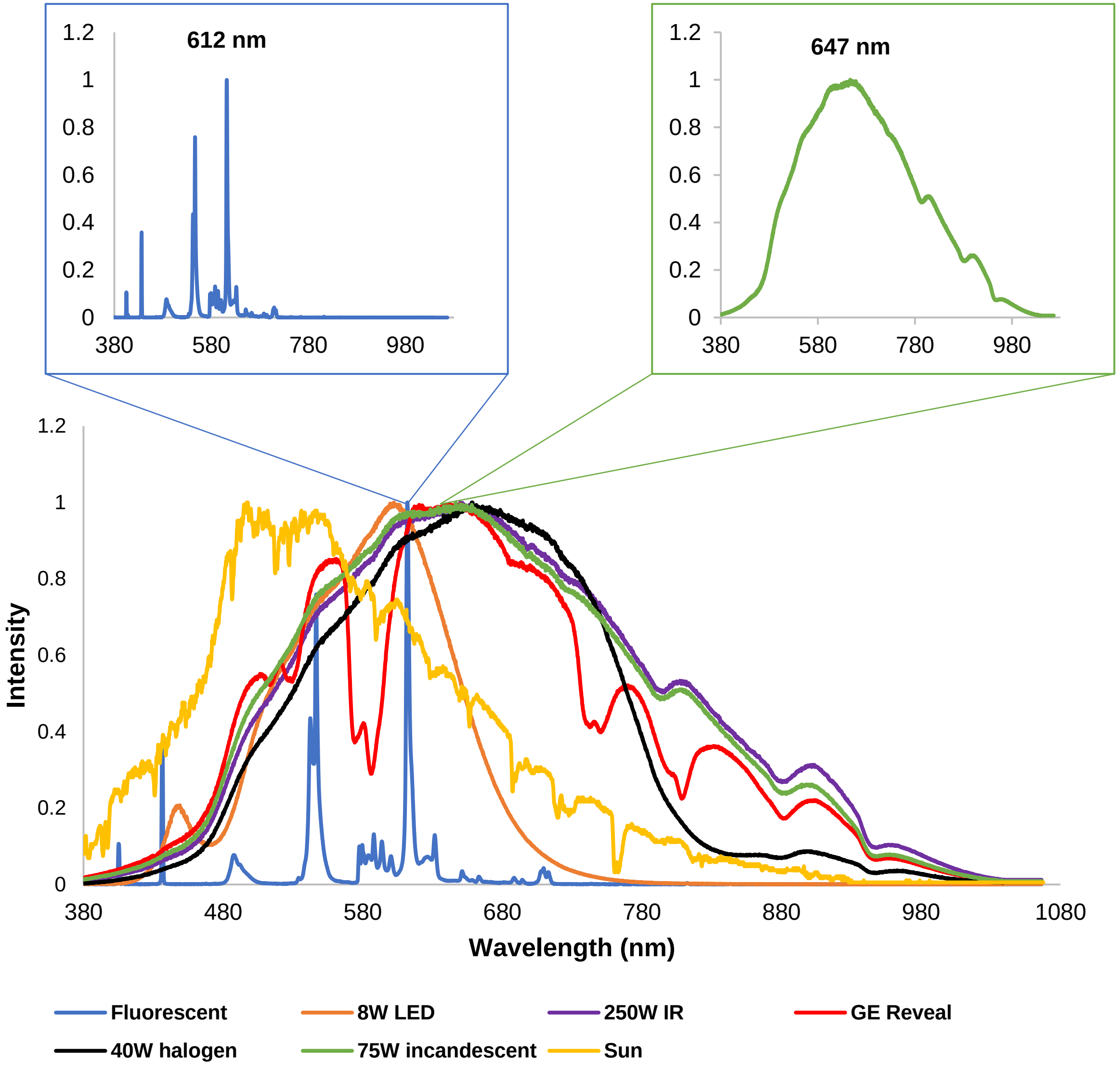
- Uses the wavelength of maximum emission (λ_{max})

$$\boxed{\lambda_{max} = b/T}$$

- b = Wien's proportionality constant
- T = temperature in K

λ_{max} determined for each emitter and temperature calculated via Wien and Planck methods.

Emitter	λ_{max} (nm)	Wien Temp. (K)	Planck Temp. (K)	Average	Standard deviation
Sun	496.90	5816.1	5835	5825.5	13.39
8W LED	602.45	4797.1	4812	4804.5	10.56
Fluorescent	611.98	4722.4	4738	4730.2	11.03
GE Reveal	646.64	4469.2	4484	4476.6	10.44
75W incandescent	646.64	4469.2	4485	4477.1	11.15
250W IR	649.97	4446.4	4464	4455.2	12.47
40W halogen	658.17	4391.0	4406	4398.5	10.64



Blackbody Emitters: Determination of temperature

Planck temperature

Planck's equation was fit to each emission spectrum to determine the **temperature**

$$\boxed{\frac{dP}{d\lambda} = 8\pi hc/\lambda^5 (e^{\left(\frac{hc}{\lambda kT}\right)} - 1)}$$

$\frac{dP}{d\lambda}$ = intensity

h = Planck's constant

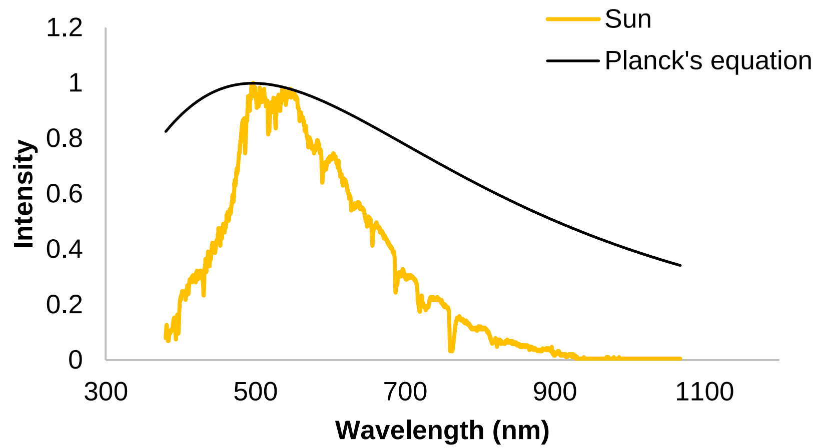
c = speed of light

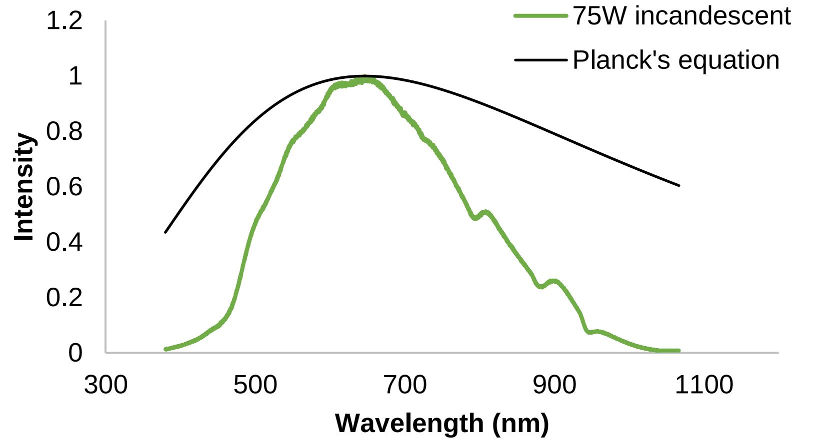
k = Boltzmann constant

λ = wavelength

λ_{max} determined for each emitter and temperature calculated via Wien and Planck methods.

Emitter	λ_{max} (nm)	Wien Temp. (K)	Planck Temp. (K)	Average	Standard deviation
Sun	496.90	5816.1	**5835**	5825.5	13.39
8W LED	602.45	4797.1	**4812**	4804.5	10.56
Fluorescent	611.98	4722.4	**4738**	4730.2	11.03
GE Reveal	646.64	4469.2	**4484**	4476.6	10.44
75W incandescent	646.64	4469.2	**4485**	4477.1	11.15
250W IR	649.97	4446.4	**4464**	4455.2	12.47
40W halogen	658.17	4391.0	**4406**	4398.5	10.64





The emission spectra of the **Sun** and the **incandescent bulb** showed the most correlation to Planck's equation.

Blackbody Emitters: Determination of temperature

Planck temperature

Planck's equation was fit to each emission spectrum to determine the **temperature**

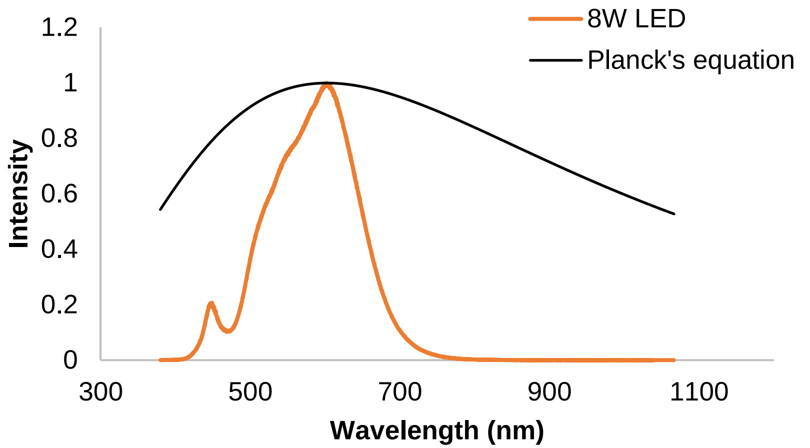
$$\frac{dP}{d\lambda} = 8\pi hc/\lambda^5\left(e^{\left(\frac{hc}{\lambda kT}\right)}-1\right)$$

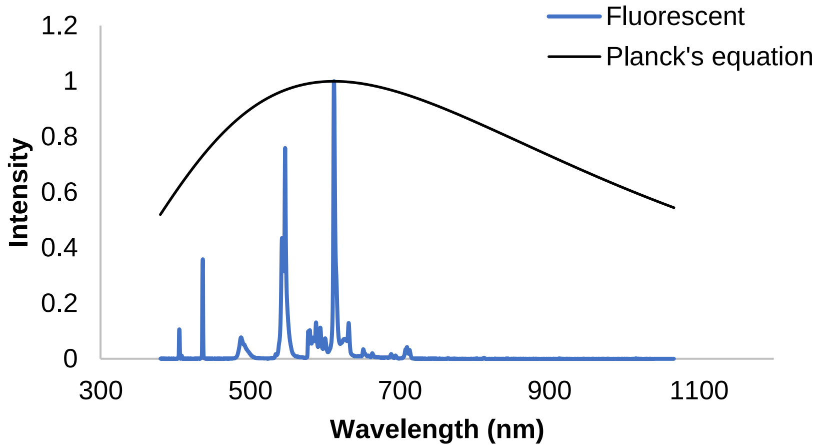
$\frac{dP}{d\lambda}$ = intensity
h = Planck's constant
c = speed of light
k = Boltzmann constant
λ = wavelength

1st hypothesis

λ_{max} determined for each emitter and temperature calculated via Wien and Planck methods.

Emitter	λ_{max} (nm)	Wien Temp. (K)	Planck Temp. (K)	Average	Standard deviation
Sun	496.90	5816.1	**5835**	5825.5	13.39
8W LED	602.45	4797.1	**4812**	4804.5	10.56
Fluorescent	611.98	4722.4	**4738**	4730.2	11.03
GE Reveal	646.64	4469.2	**4484**	4476.6	10.44
75W incandescent	646.64	4469.2	**4485**	4477.1	11.15
250W IR	649.97	4446.4	**4464**	4455.2	12.47
40W halogen	658.17	4391.0	**4406**	4398.5	10.64





The emission spectra of the **8W LED** and the **fluorescent bulb** showed the worst correlation to the blackbody emission profile.

Blackbody Emitters: Determination of temperature

Planck temperature

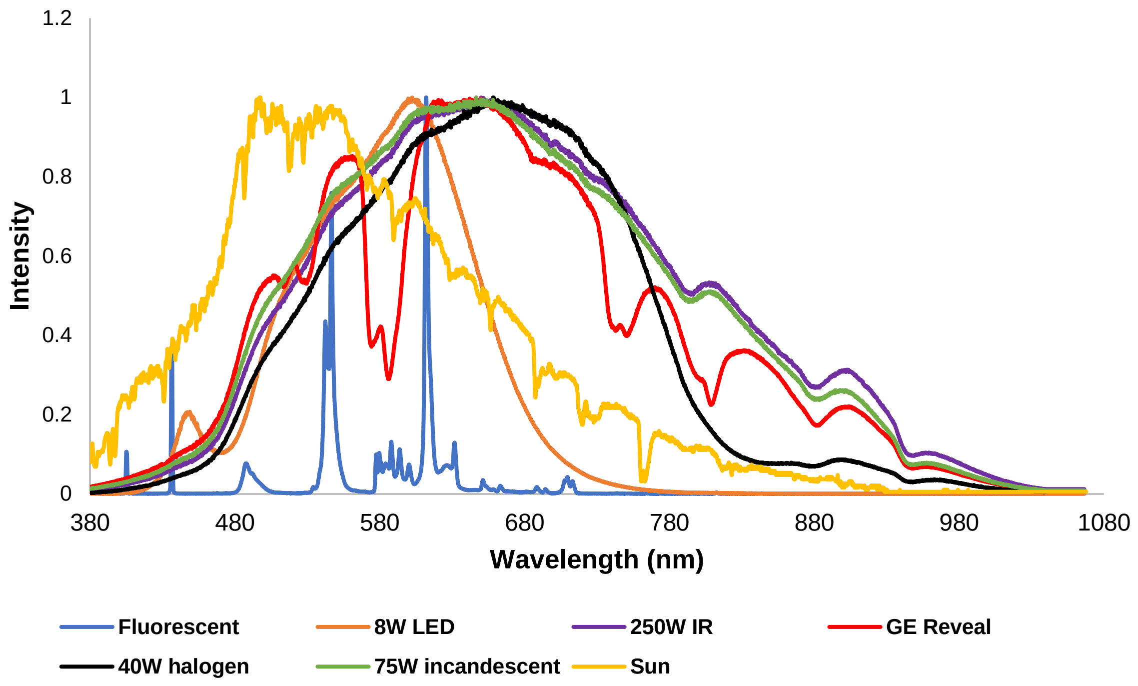
Planck's equation was fit to each emission spectrum to determine the **temperature**

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

$\frac{dP}{d\lambda}$ = intensity
h = Planck's constant
c = speed of light
k = Boltzmann constant
λ = wavelength

λ_{max} determined for each emitter and temperature calculated via Wien and Planck methods.

Emitter	λ_{max} (nm)	Wien Temp. (K)	Planck Temp. (K)	Average	Standard deviation
Sun	496.90	**5816.1**	**5835**	**5825.5**	13.39
8W LED	602.45	4797.1	4812	4804.5	10.56
Fluorescent	611.98	4722.4	4738	4730.2	11.03
GE Reveal	646.64	4469.2	4484	4476.6	10.44
75W incandescent	646.64	4469.2	4485	4477.1	11.15
250W IR	649.97	4446.4	4464	4455.2	12.47
40W halogen	658.17	4391.0	4406	4398.5	10.64



Planck and Wien temperature matched relatively closely

- Standard deviation values ≈10
- Both showed the Sun as the hottest emitter

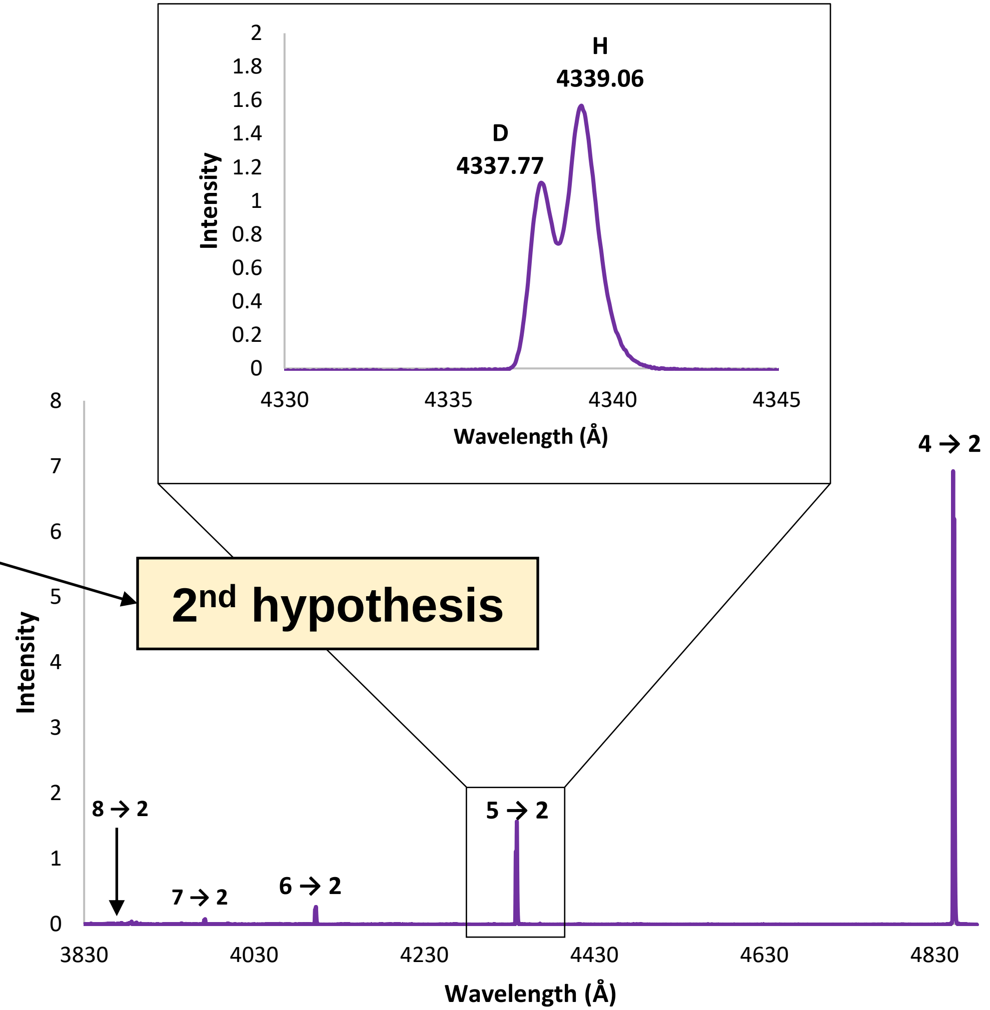
Line Spectra: λ_{max} and energy level transitions

5 emission lines observed

- Each line splits into 2 separate peaks for **hydrogen** and **deuterium**

Wavelength of maximum emission (λ_{max}) was determined for each line

- λ_{max} used to find energy level transition
- **Intensity** decreases as transition **energy** increases
  - Smaller population in high energy excited states



Wavelength and energy of each energy level transition observed in the line spectra of deuterium and hydrogen.

Deuterium (^2H)			Hydrogen (^1H)			Energy level transition
λ_{max} (nm)	Energy (eV)	Intensity	λ_{max} (nm)	Energy (eV)	Intensity	
485.215	2.5555	6.92	485.335	2.5549	6.20	n = 4 → 2
433.777	2.8585	1.09	433.906	2.8577	1.57	n = 5 → 2
410.177	3.0230	0.22	410.285	3.0222	0.26	n = 6 → 2
397.136	3.1223	0.06	397.240	3.1215	0.07	n = 7 → 2
389.094	3.1868	0.15	389.190	3.1860	0.02	n = 8 → 2

Line Spectra: Rydberg constant

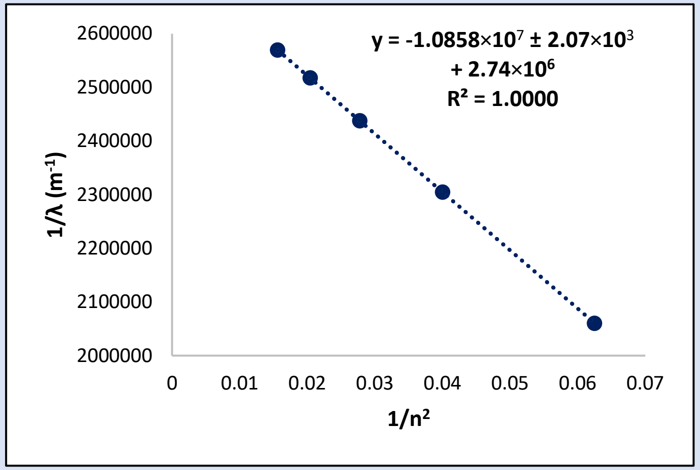
Experimental calculation

Determined **experimentally** using the slope of the **linear regression** of the Rydberg equation

$$\frac{1}{\lambda} = \mathfrak{R}_H \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2}\right)$$

Rydberg constant

1/λ was plotted as a function of $1/n^2$



Linear regression of the Rydberg equation for the hydrogen atom. Slope of the line represents $\mathfrak{R}_H$.

Theoretical calculation

Calculated **theoretically** via Bohr's equation

$$\mathfrak{R} = \mu e^4 / 8{\varepsilon_0}^2 h^3 c$$

μ = reduced mass
e = elementary charge
ε_0= permittivity of free space
h = Planck's constant
c = speed of light

Theoretical and experimental Rydberg constants for hydrogen and deuterium with percent difference.

Atom	Experimental R (m^{-1})	Theoretical R (m^{-1})	% difference
Hydrogen	$1.0858\times 10^7 \pm 2.07\times 10^3$	1.0973×10^7	8.008
Deuterium	$1.0860\times 10^7 \pm 1.53\times 10^3$	1.0976×10^7	8.005

Line Spectra: Ionization energy and mass of deuterium

Ionization energy (IE) is the energy required to remove an electron from an atom

- Determined using the **Rydberg equation**
  - n_2 = ∞ for an electron being removed
  - n_1 = 1 for the ground state

$$\frac{1}{\lambda} = \Re_H \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2}\right)$$

$$\frac{1}{\lambda} = \Re_H$$

Theoretical and experimental ionization energies for hydrogen and deuterium.

Atom	Experimental IE (eV)	Theoretical IE (eV)	% difference
Hydrogen	13.472 ± 0.0026	13.606	0.985
Deuterium	13.476 ± 0.0019	13.610	0.988

The **nuclear mass of deuterium** was determined experimentally using the ratio of Rydberg constants for deuterium (R_D) and hydrogen (R_H)

- μ = reduced mass
- m_e = mass of an electron
- m_N= mass of nucleus

Theoretical mass of deuterium was assumed to be $\boldsymbol{M_D} = {}^2\boldsymbol{H}$

$$\frac{R_D}{R_H} = \frac{R\mu_D}{R\mu_H}$$

$$\frac{R_D}{R_H} = \frac{\mu_D}{\mu_H}$$

$$\mu_D = \frac{m_e m_N}{m_e + m_N}$$

Theoretical and experimental nuclear mass of deuterium with percent difference.

Experimental mass of deuterium (kg)	Theoretical mass of deuterium (kg)	% difference
$2.976\times 10^{-27} \pm 2.56\times 10^{-30}$	3.345×10^{-27}	10.88

Conclusions

Speed of Light

Increasing distance traveled increases the accuracy of measurements
- *Light has to travel a small distance to reach detector 1, decreasing accuracy of speed*

Blackbody Radiation

The **Sun** and **incandescent bulb** followed Planck's model best
Sun was the **hottest** blackbody emitter in both Wien and Planck models
- *Actual core temperature = 15 million K*

Line Emission Spectra

Line intensities decrease at short wavelengths
- *Lines are not as sharp/narrow as they should be in theory*

Deuterium has a larger **Rydberg constant** and **ionization energy** than hydrogen
- *Rydberg equation only works for isotopes of hydrogen*

Thanks for watching!

References

1. Wagner, E. P. Let There Be Light: Investigations of Light, Blackbody Emitters, and Line Spectra. 2019.
2. Crouch, S. R., Holler, F. J., and Skoog, D. A. An Introduction to Optical Atomic Spectrometry. *In Principles of Instrumental Analysis*. 6th edition.; Thomson Brooks/Cole 2007. pp. 215-229.
3. Kuhn, H., Försterling, H., and Waldeck, D. H. Emission of Light. In *Principles of Physical Chemistry*. 2nd edition.; John Wiley & Sons, Inc 2009. pp 261-279.
4. Blackbody Radiation. In The SAO Encyclopedia of Astronomy. *Cosmos*. *Swinburne University of Technology.* https://astronomy.swin.edu.au/cosmos/b/blackbody+radiation.
5. Atomic Spectroscopy, Spectral Line Shapes, etc. NIST Physical Measurement Laboratory, 2019. https://www.nist.gov/pml/atomic-spectroscopy-compendium-basic-ideas-notation-data-and-formulas/atomic-spectroscopy-6.
6. Incandescent and Fluorescent Lighting. *Canon Science Lab*. https://global.canon/en/technology/s_labo/light/002/02.html.
7. Hochman, S. "ICP-OES: Why spectral lines are true peaks and how this can fool the user," *The Winnower*. https://thewinnower.com/papers/217-icp-oes-why-spectral-lines-are-true-peaks-and-how-this-can-fool-the-user.

University of Pittsburgh

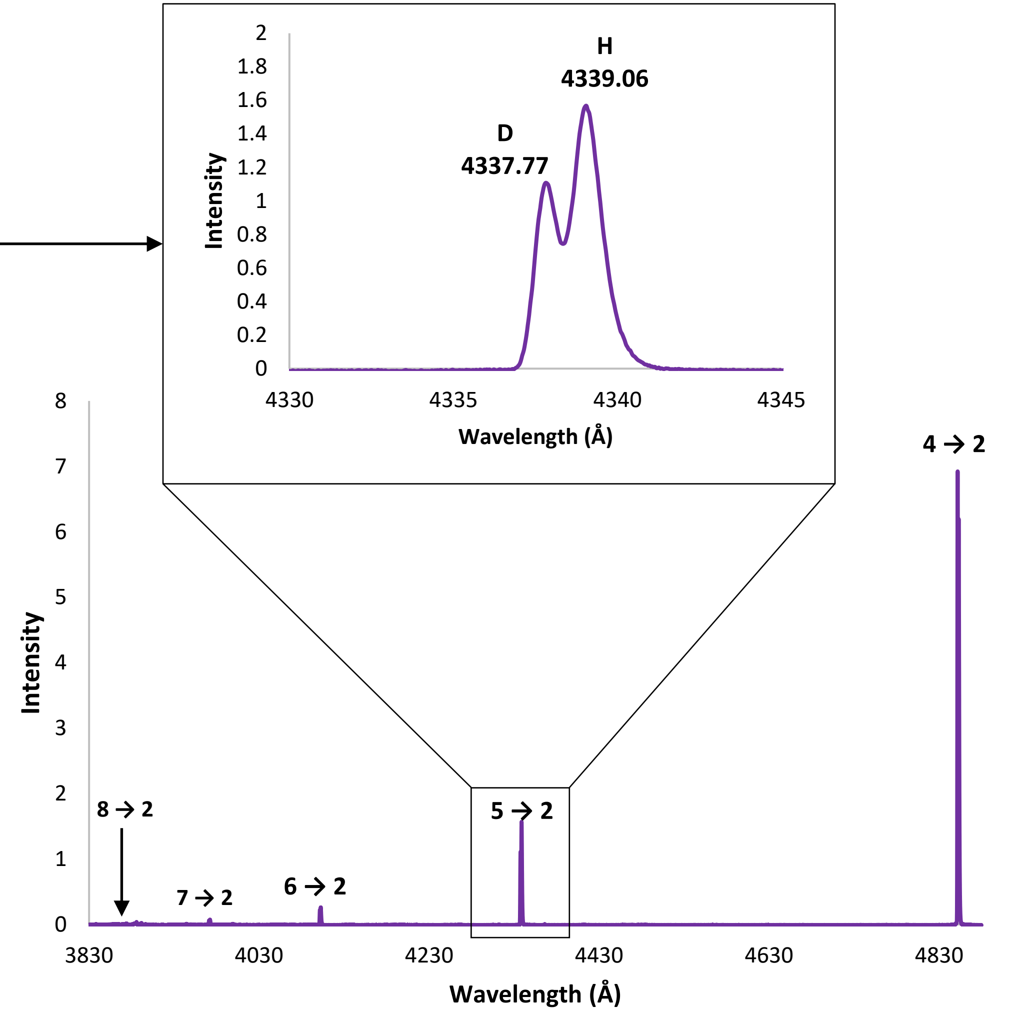
Line Spectra: λ_{max} and energy level transitions

Theory predicts sharp and narrow lines

Pressure broadening: collisions of emitting atoms with neighboring particles

Doppler broadening: thermal motion of emitting atoms

Uncertainty effect: large amount of uncertainty in lifetime of each transition state/excited state



Wavelength and energy of each energy level transition observed in the line spectra of deuterium and hydrogen.

Deuterium (^2H)			Hydrogen (^1H)			Energy level transition
λ_{max} (nm)	Energy (eV)	Intensity	λ_{max} (nm)	Energy (eV)	Intensity	
485.215	2.5555	6.92	485.335	2.5549	6.20	n = 4 → 2
433.777	2.8585	1.09	433.906	2.8577	1.57	n = 5 → 2
410.177	3.0230	0.22	410.285	3.0222	0.26	n = 6 → 2
397.136	3.1223	0.06	397.240	3.1215	0.07	n = 7 → 2
3890.94	3.1868	0.15	3891.90	3.1860	0.02	n = 8 → 2