PHAS1202
(Atoms), STARS and THE UNIVERSE

Prof. Raman Prinja

PHAS 1202 – Part TWO

1) **Stellar Astrophysics**
2) **Galaxies and Cosmology**

- **3 hours** of lectures per week (as normal)

Mon. 11:00-13:00 ______________

Wed. 10:00 - 11:00 ______________

+ 'Problem solving tutorials' → online timetable

- **Notes –** Partial lectures PDF slides on moodle (download them!)

  ……BUT

  there'll be additional goodies during the lectures!

Lecturecast?? – I'll try…but no promises it'll work!

Astrophysics **ICA** in December (based on Practice problem sheets + PSTs)

PHAS 1202 -- Astrophysics

Topics covered: (Introductions!)

- Radiation, luminosity, effective temperature
- Stellar spectra and classification of stars
- Stellar evolution
- Galaxies and large-scale structure in the Universe
- Cosmology (observational) – Big Bang model

Reading list

Freedman & Kaufmann, “Universe” (>8th ed., Freeman, 2008)

Zeilik & Gregory, “Introductory Astronomy and Astrophysics (>4th ed., Thomson Learning, 1998)

Contact details:

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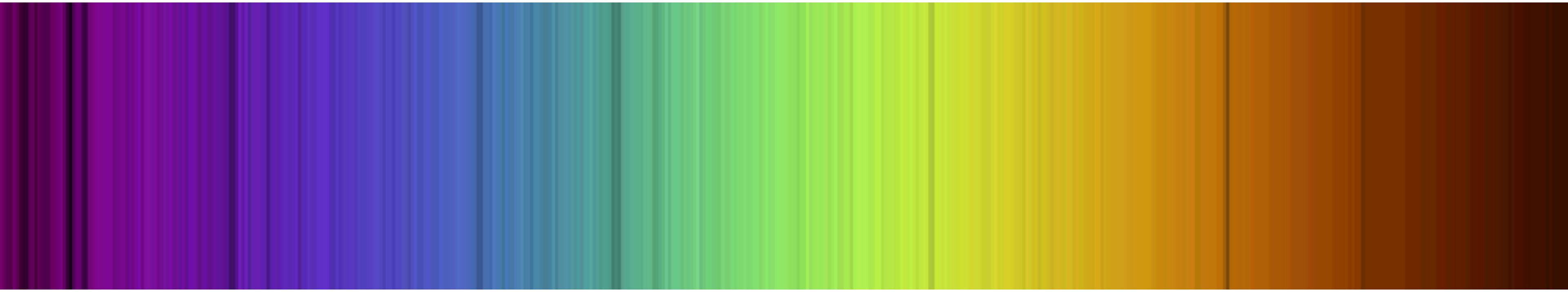
- **Best to use e-mail first:**
  rkp AT star.ucl.ac.uk   (AT = @)



1) Introduction to stars and **RADIATION**

...tremendous variety of stars

... E.g. **Massive stars →**

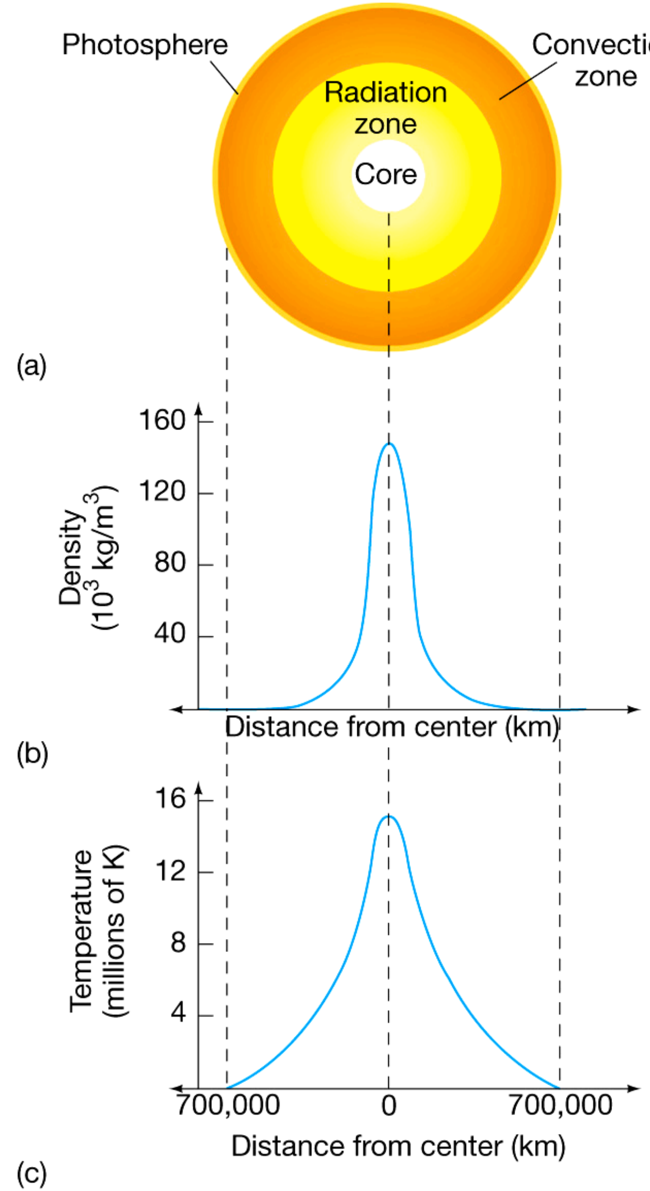
- 20 – 100 times more massive than the Sun
- 20 – 100 larger than the Sun
- up to a million times more luminous

Stellar properties

	Sun	stars
Mass	$1 M_\odot = 2 \times 10^{30}\,\mathrm{kg}$	$\sim 0.1 - 40\, M_\odot$
Radius	$1 R_\odot = 7 \times 10^{8}\,\mathrm{m}$	$\sim 0.1 - 20\, R_\odot$
Temperature	$5800\,\mathrm{K}$	$\sim 2500 - 45000\,\mathrm{K}$
Chemical composition	$70\%\,\mathrm{H}, 28\%\,\mathrm{He}, 2\%\,\mathrm{Metals}$	
Magnetic field	$\sim 0.1\,\mathrm{T}$ in spots	$\sim 0.5\,\mathrm{T}$
Rotational velocity	$20 \mathrm{km\,s}^{-1}$	$\lesssim 500 \mathrm{km\,s}^{-1}$
Age	$\sim 4.5 \times 10^{9}$ years	$\lesssim 13 \times 10^{9}$ years

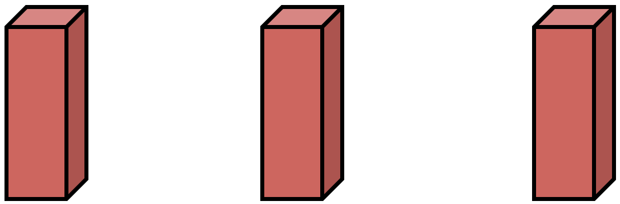
(Insert)

Main body of the Sun is defined by the dominant transport process



Recall...

... light can be thought of as packets (or ‘quanta’) of energy called ***photons***. Photon energy, *E*:



$$E = h\nu = \frac{hc}{\lambda}$$

$\boldsymbol{\nu}$ = frequency (Hz) $\boldsymbol{h}$ = Planck’s constant (= 6.63 x 10^{-34} J s)

high frequency

$\Rightarrow$ short wavelength

$\Rightarrow$ high energy

Examples of particle nature of light can be seen in:

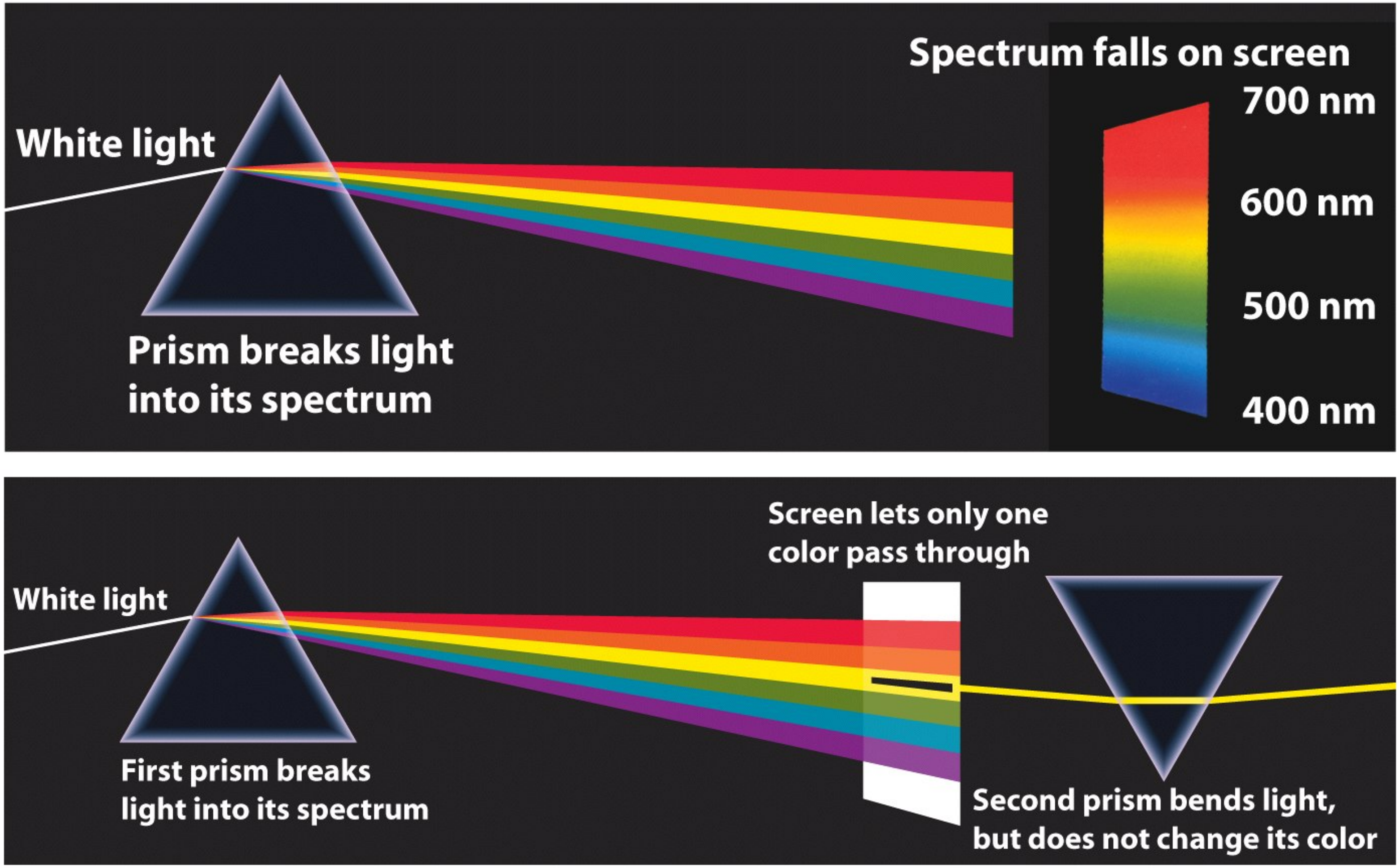
• Photo-electric effect

• Atomic spectra

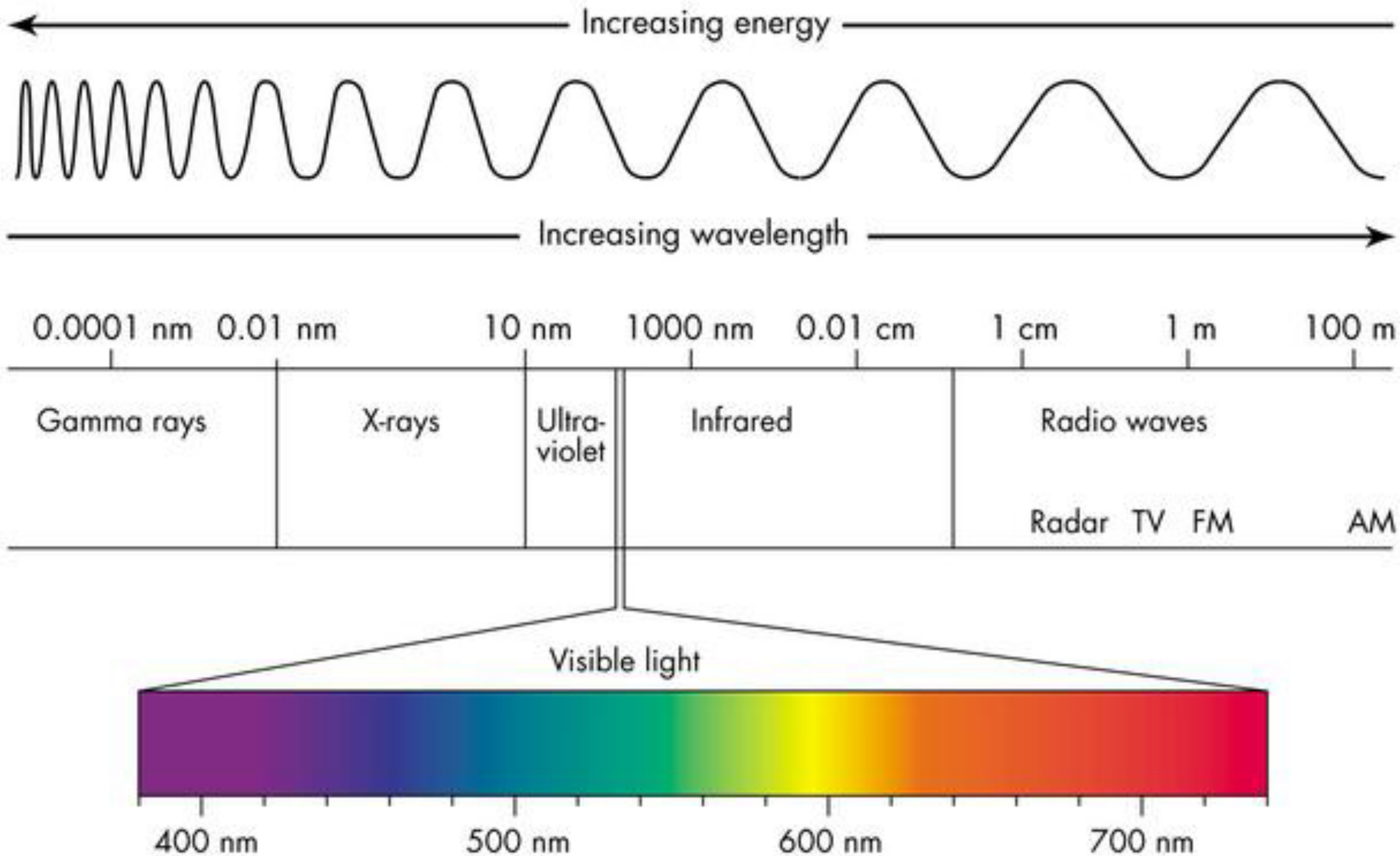
(e.g. previous notes...)

Light: spectrum and color

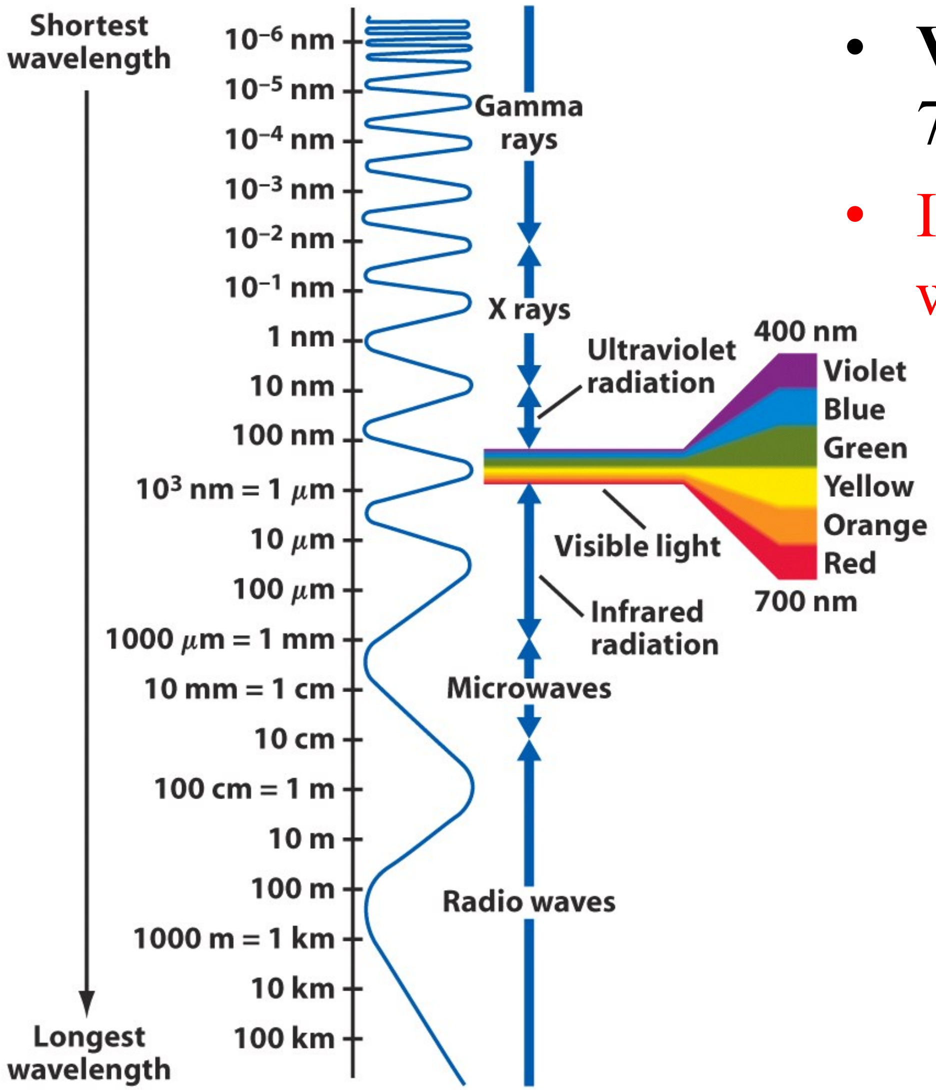
- Newton found that the white light from the Sun is composed of light of different color, or spectrum (1670).



Electromagnetic spectrum



Electromagnetic Spectrum



- **Visible light** falls in the 400 to 700 nm range
- In the order of decreasing wavelength
  - Radio waves: 1 m
  - Microwave: 1 mm
  - Infrared radiation: 1 μm
  - Visible light: 500 nm
  - Ultraviolet radiation: 100 nm
  - X-rays: 1 nm
  - Gamma rays: 10^{-3} nm

Units

Wavelength: SI units – metre, m

Optical/UV: **Angstrom, A** 1A = 10^{-10} m = 10^{-8} cm = 0.1nm

nanometre, nm 1nm = 10^{-9} m

Infrared: **micron, μm** 1μm = 10^{-6} m

Frequency: SI units – Hertz, Hz

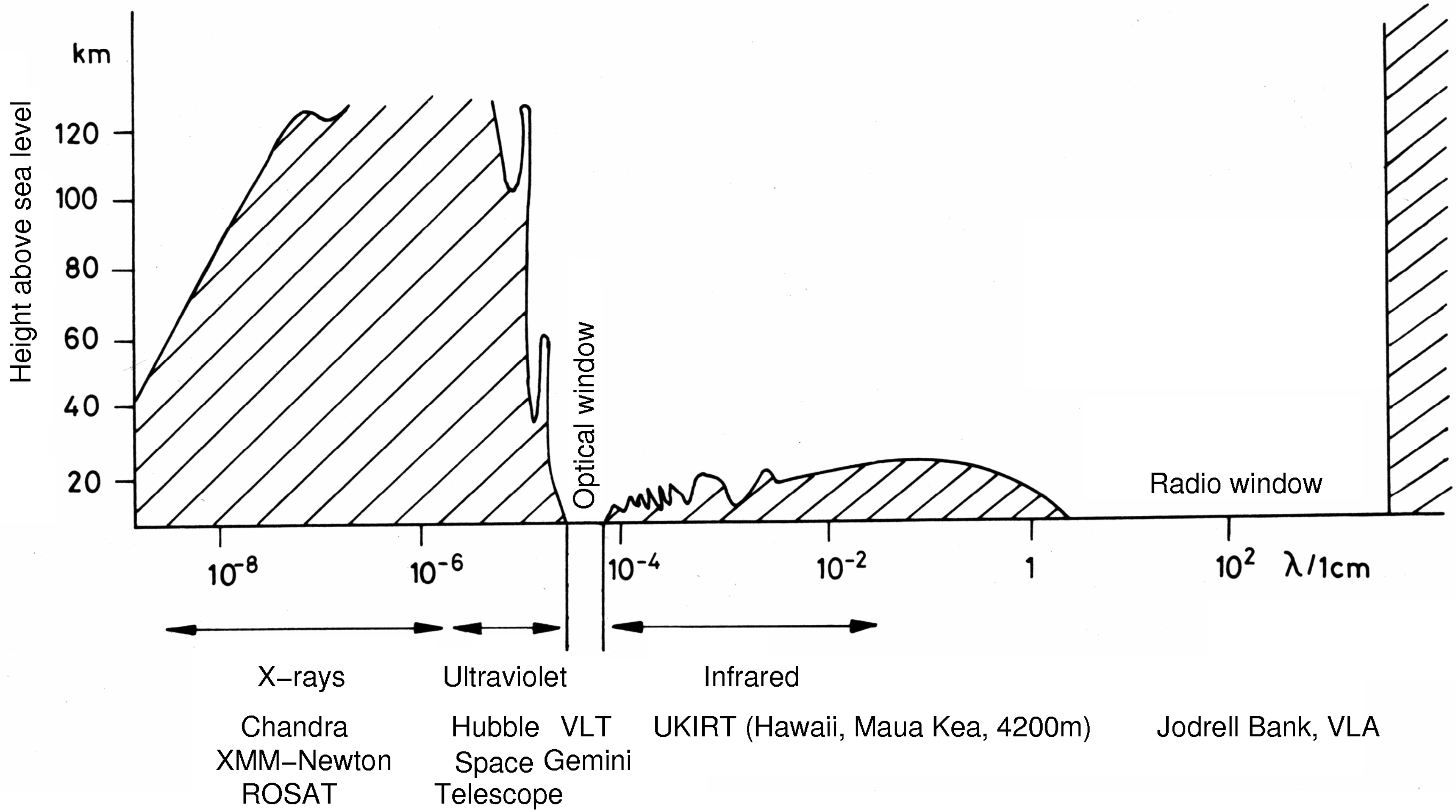
Radio: **Gigahertz, GHz** 1GHz = 10^{9} Hz

Energy: SI units – Joules, J

X-ray: **electron volts, eV** 1eV = 1.6×10^{-19} J

1keV = 1.6×10^{-16} J

Penetration depths through the Earth atmosphere

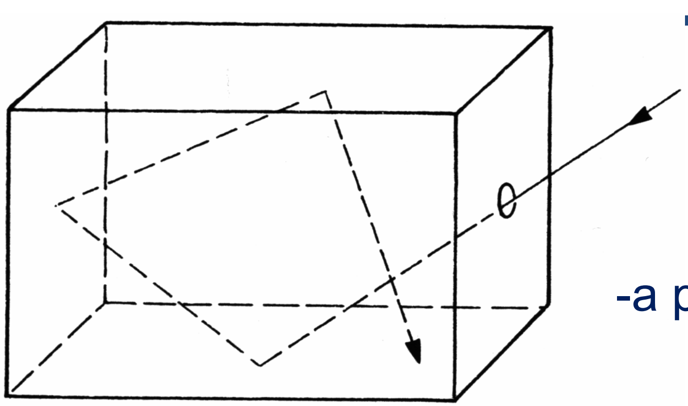


RECALL - 'Thermal' spectrum of radiation: Blackbody

: A body which absorbs all radiation incident upon it.
To be in perfect thermal equilibrium, it must also emit radiation at the same rate it absorbs it
➔ its temperature is maintained

Example: Perfectly insulated enclosure within which radiation is in equilibrium with the enclosure walls
➔ observe blackbody radiation through a pinhole

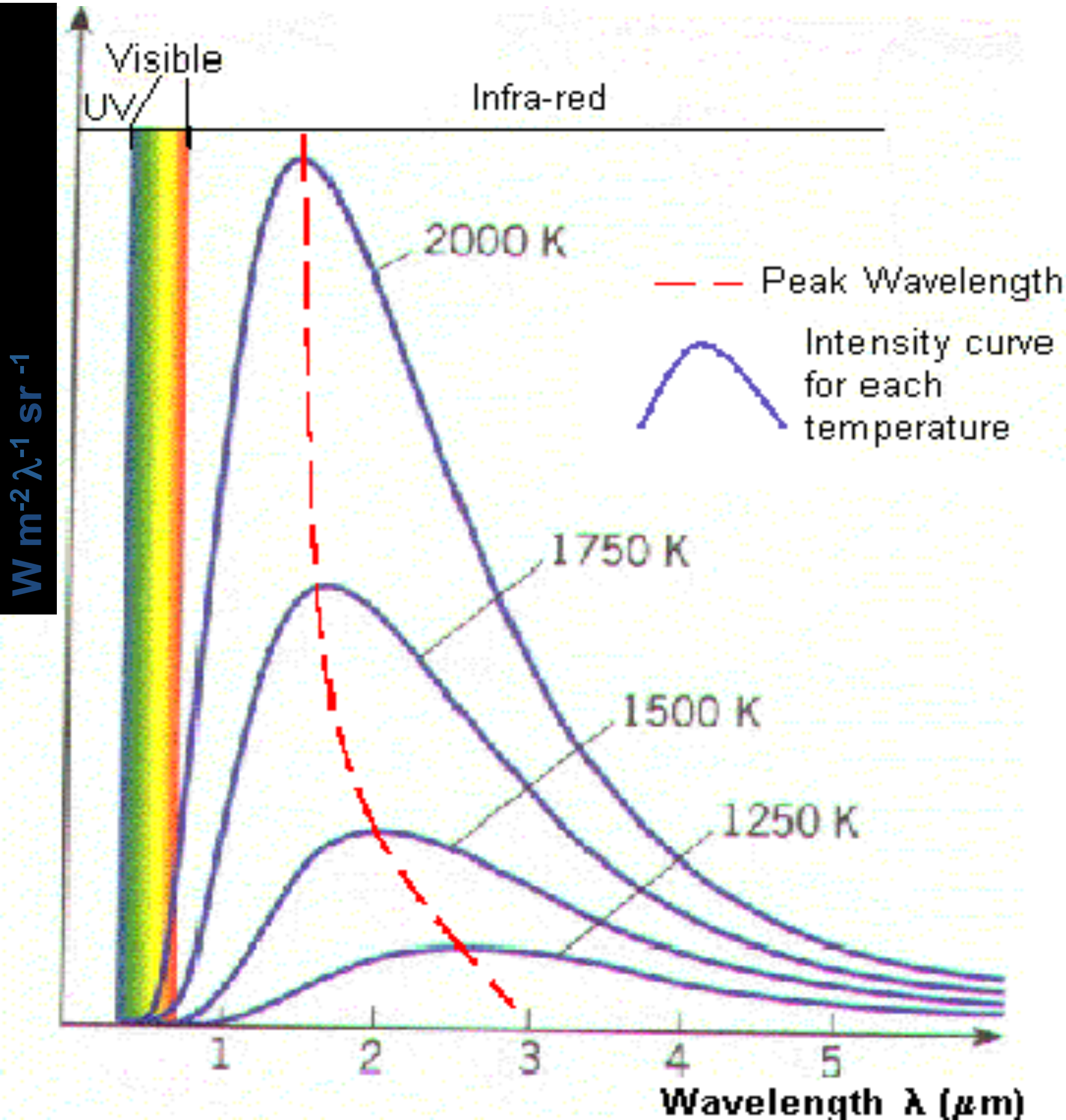
Gases in the interior of stars are opaque to all radiation



➔ Surfaces of stars emit very closely to a *blackbody spectrum*

-a perfect absorber/emitter, absorbs all intercepted photons

'Thermal' spectrum of radiation: Blackbody



In 1900 Planck postulated e.m. energy propagates in quanta, and derived the blackbody radiation law:

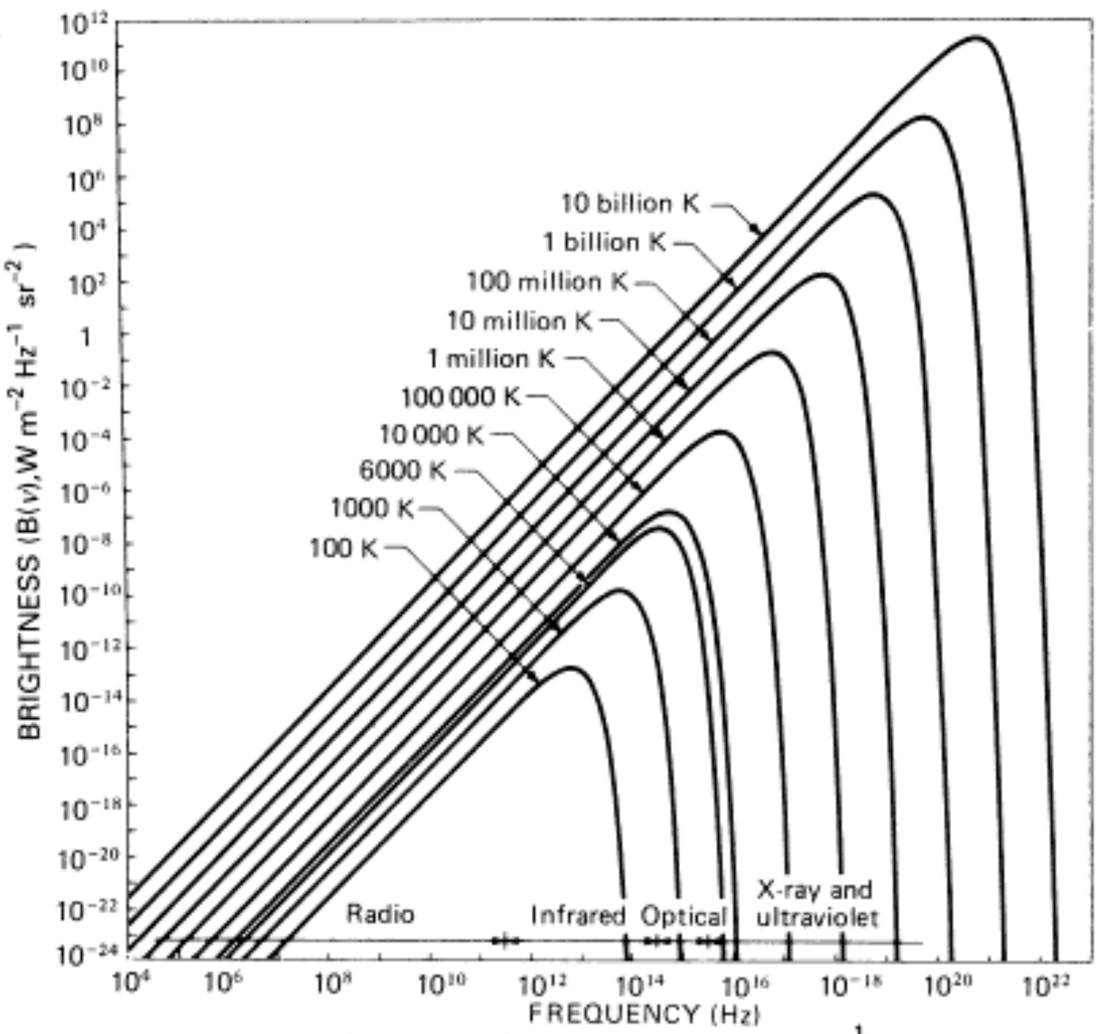
$$I(\lambda) = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT} - 1}\right]$$

where $I(\lambda)$ is the intensity emitted by a blackbody at temperature T in the range of wavelength λ and $\lambda+\Delta\lambda$

h: Planck's constant
c: speed of light
k: Boltzmann's constant
T: temperature in Kelvin

‘Thermal’ spectrum of radiation: Blackbody

Alternatively, we can express the blackbody radiation law (also called Planck’s function) in terms of frequency:

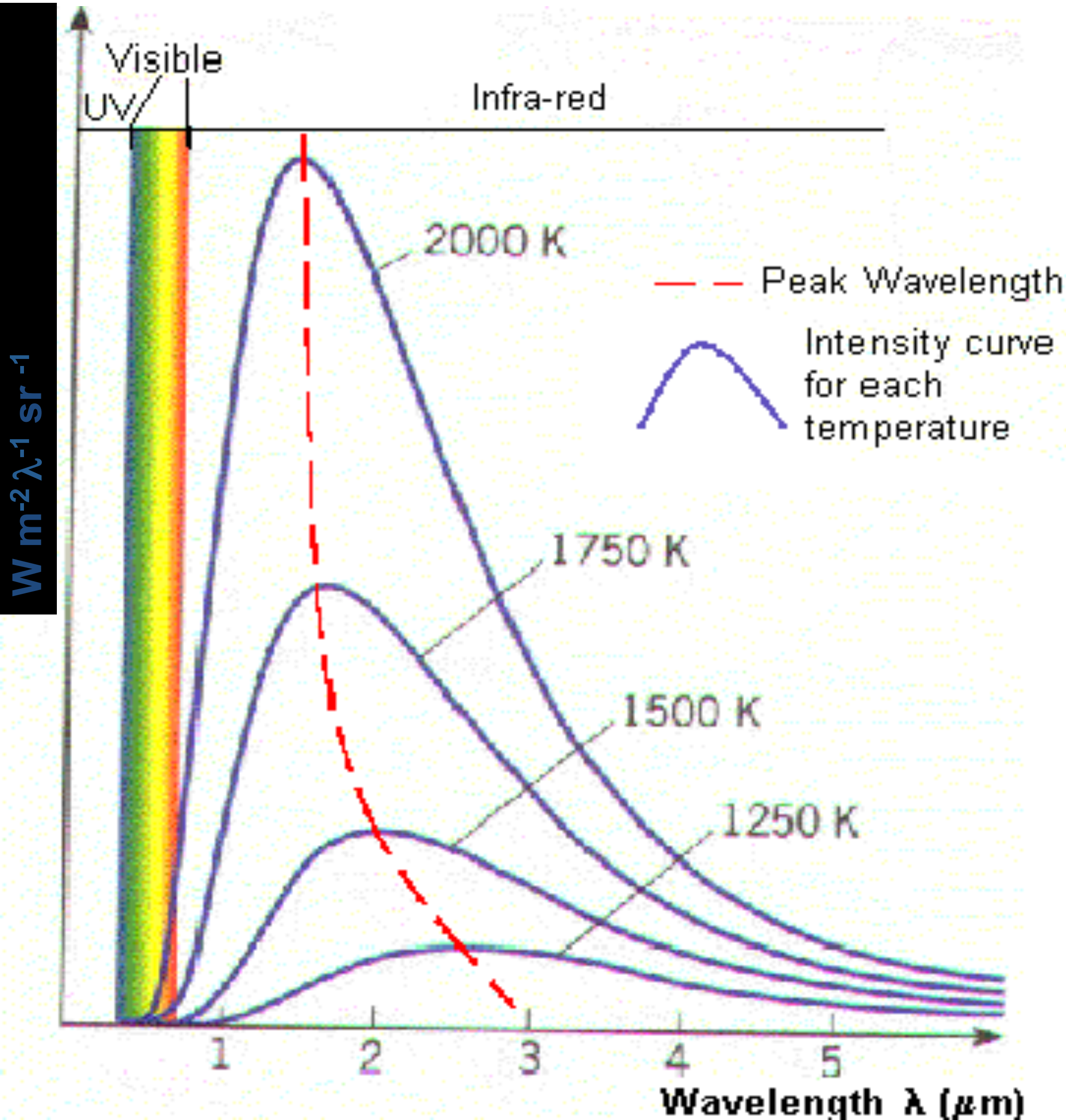


$$I(\nu) = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT}-1}\right]$$

where $I(\nu)$ is the intensity emitted by a blackbody at temperature T in the range of frequency ν and $\nu + \Delta\nu$

h: Planck’s constant
c: speed of light
k: Boltzmann’s constant
T: temperature in Kelvin

'Thermal' spectrum of radiation: Blackbody



Wien displacement law expresses wavelength at which maximum intensity of blackbody radiation is emitted as a function of temperature; it is obtained by setting

$$\frac{dI(\lambda)}{d\lambda} = 0$$

$$\rightarrow \boxed{\lambda_{\max} \approx \frac{3\times 10^{-3}}{T}}$$

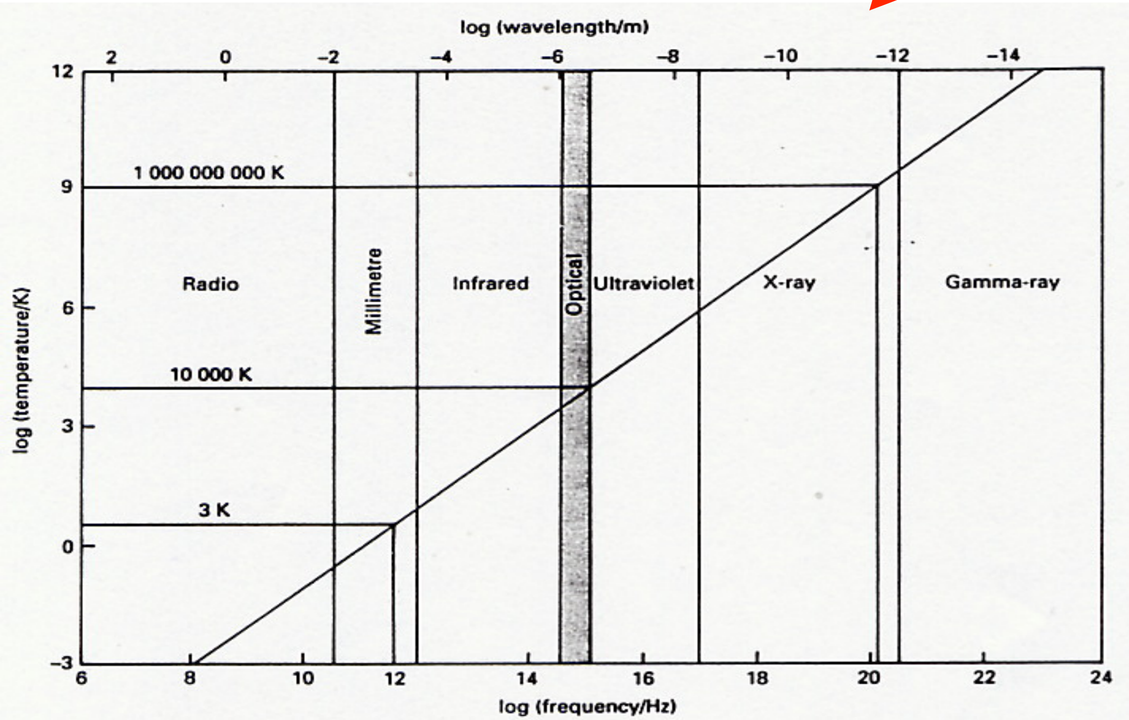
where λ_{max} in m

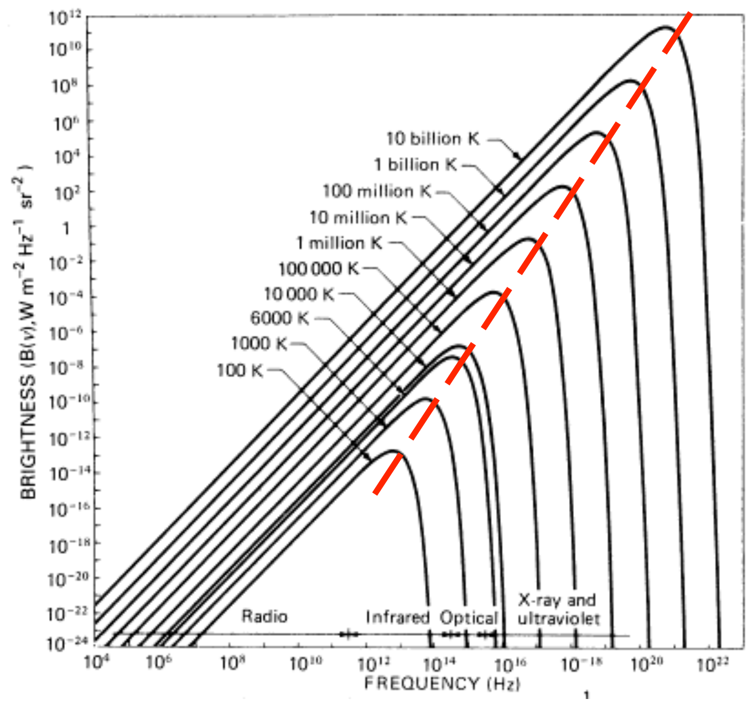
T in Kelvin

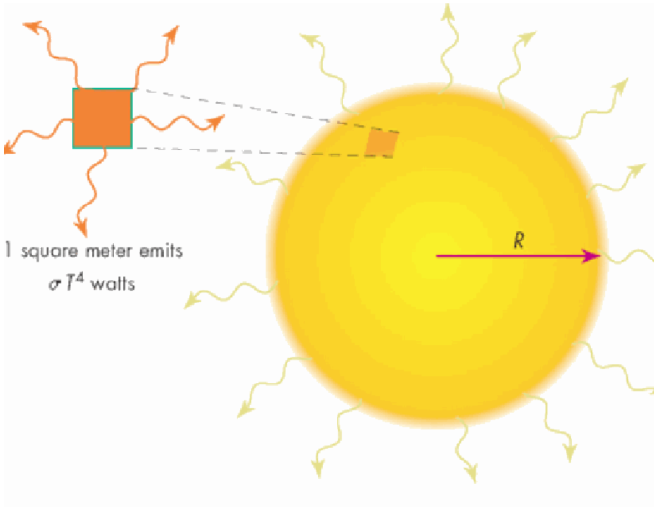
'Thermal' spectrum of radiation: Blackbody

Wien displacement law: $\boxed{\lambda_{\max} \approx \frac{3\times10^{-3}}{T}}$ or $\boxed{\nu_{\max} \approx 10^{11} T}$ (ν in Hz)

(remember $\lambda\nu = c = 3 \times 10^8$ m s^{-1})







$$flux = \sigma T^4$$

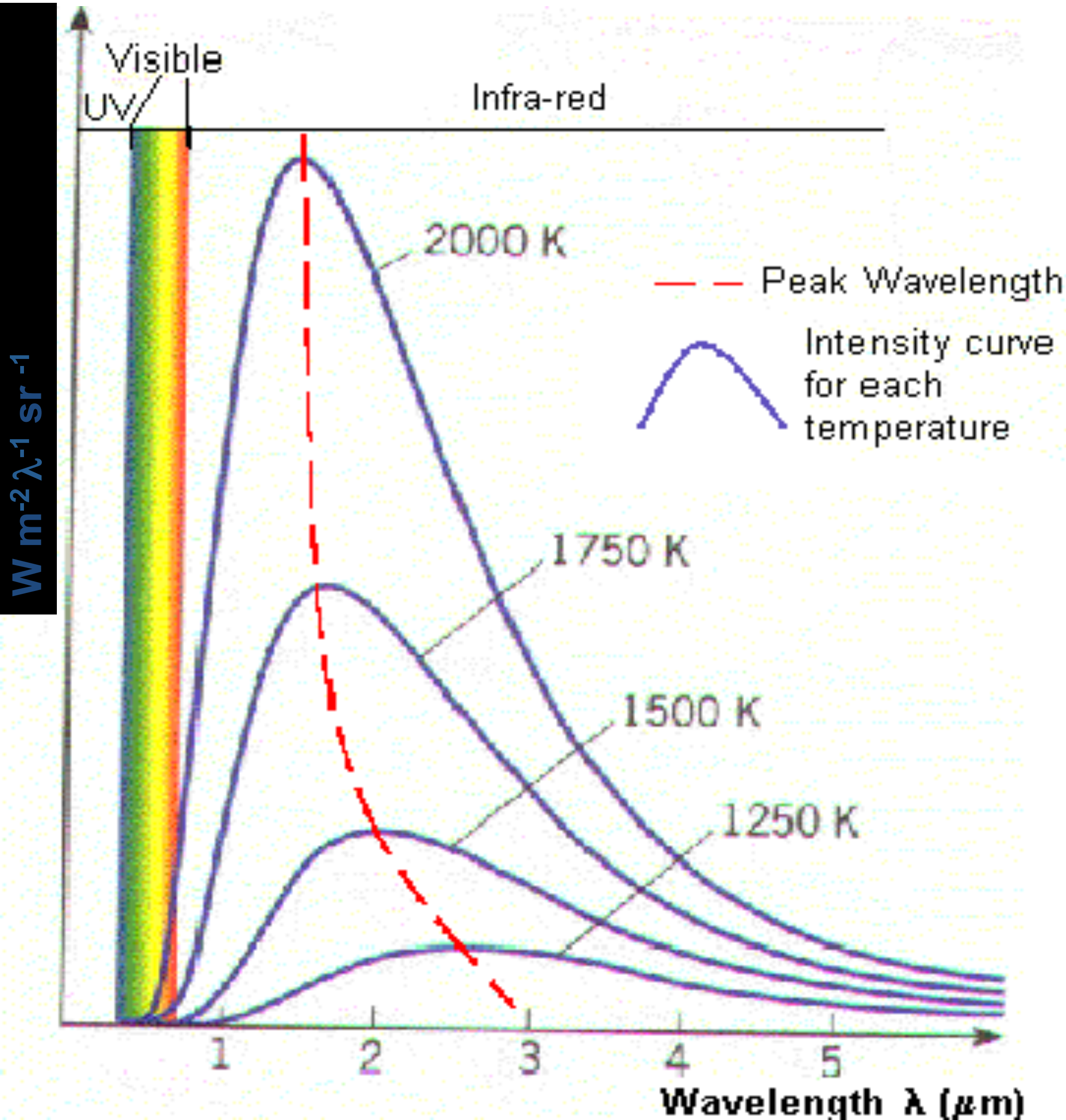
Flux is energy / unit area

Where, $\sigma = 5.67\times10^{-8}\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-4}}$

$$L = flux \bullet Area = \sigma T^4 \bullet 4\pi\, r^2$$

- The Stefan-Boltzmann Law links a star's temperature to the amount of light the star emits
  - Hotter stars emit more!
  - Larger stars emit more!
- A star's luminosity is then related to both a star's size and a star's temperature
- We need an organizational tool to keep all of this straight…

‘Thermal’ spectrum of radiation: Blackbody (7)



Stefan-Boltzmann law

Area under Planck’s curve (by integrating Planck’s function over wavelength and all solid angles) is the <u>total power emitted per unit area</u>:

W m^{-2}

$$\boxed{F(T) = \sigma T^4}$$

σ= 5.67 x 10^{-8} W m^{-2} K^{-4}

σ = Stefan-Boltzmann’s constant

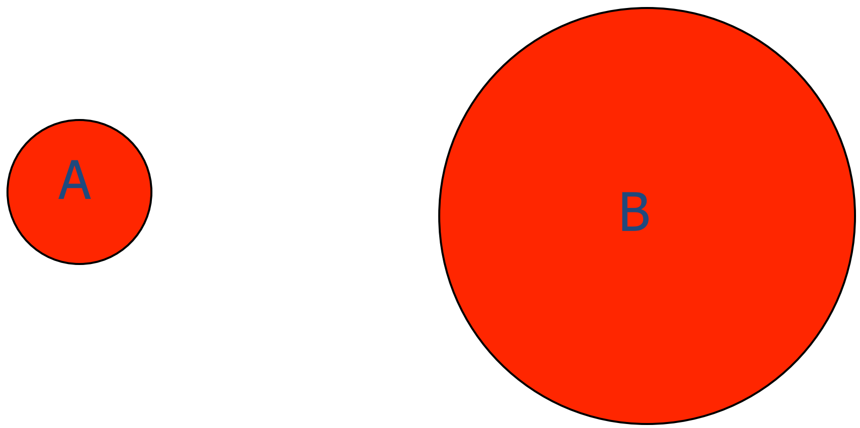
Luminosity of star of radius *R* (emitting as a blackbody)

$$\boxed{L = 4\pi R^2 \sigma T^4}$$

The Size (Radius) of a Star

We already know: flux increases with surface temperature ($\sim T^4$); hotter stars are brighter.

But luminosity also increases with size:



Star B will be brighter than star A.

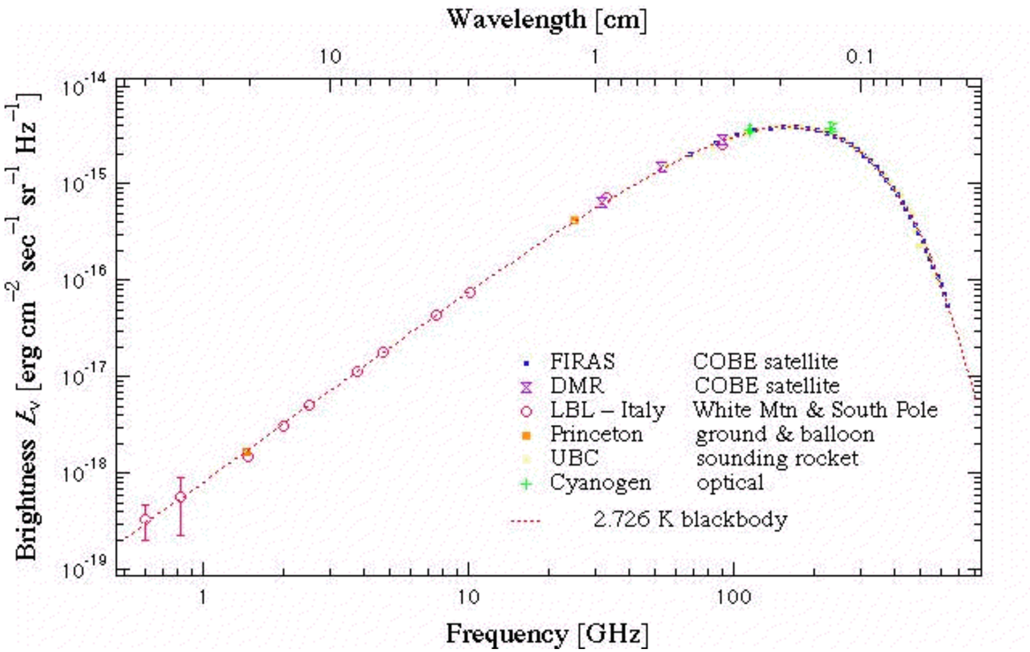
Luminosity is proportional to radius squared, $L \sim R^2$.

Quantitatively:

$$\boxed{L = \underbrace{4\pi R^2}_{\text{Surface area of the star}}\ \underbrace{\sigma T^4}_{\text{Surface flux due to a blackbody spectrum}}}$$

‘Thermal’ spectrum of radiation: Blackbody (8)

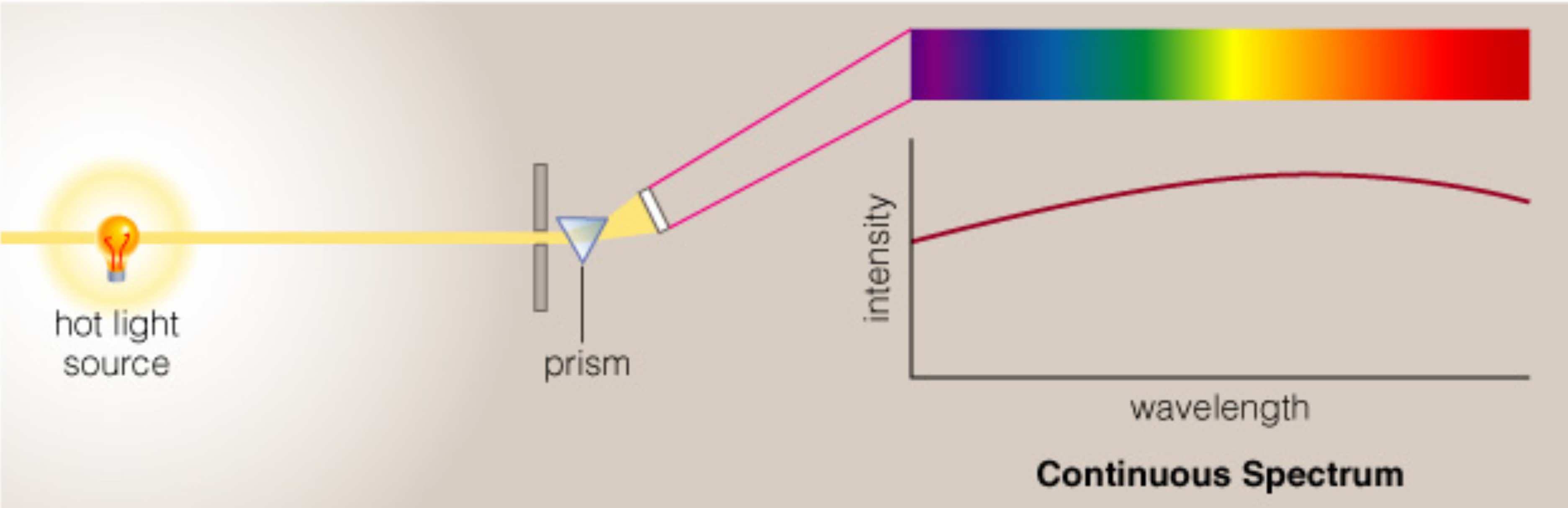
The best example of a blackbody is provided by the spectrum of the microwave background, the relic of the
Big Bang, known to be now at 2.7 K.



PHAS 1202

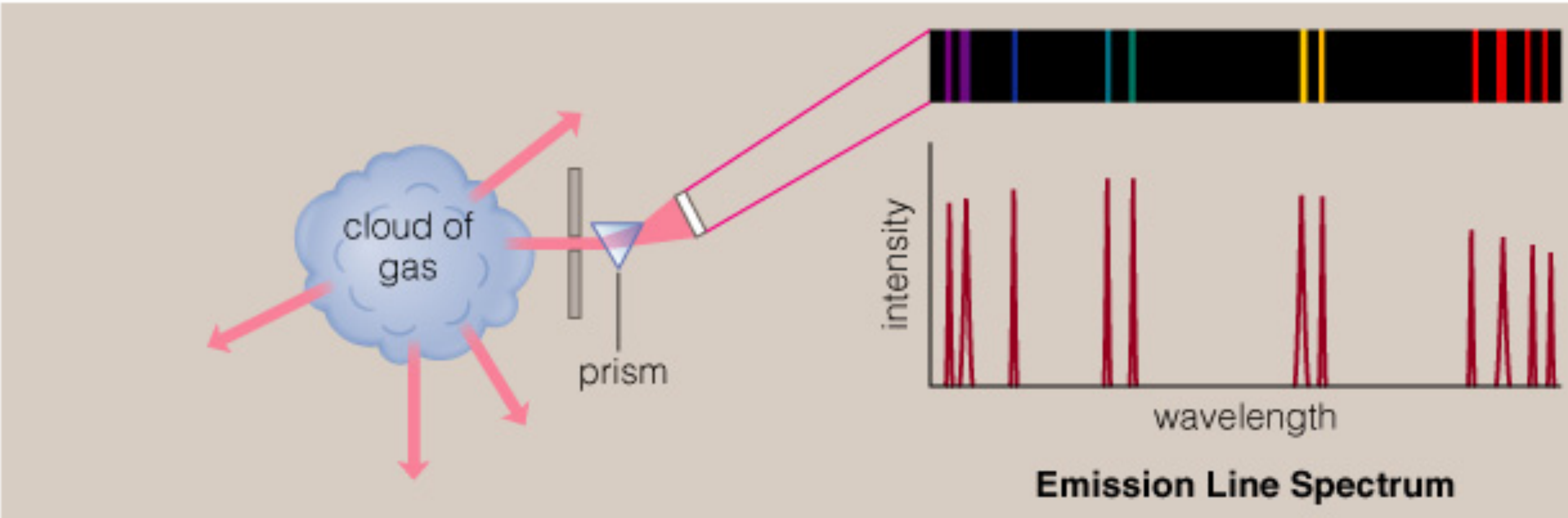
2 – Spectra and stellar classification

Continuous Spectrum



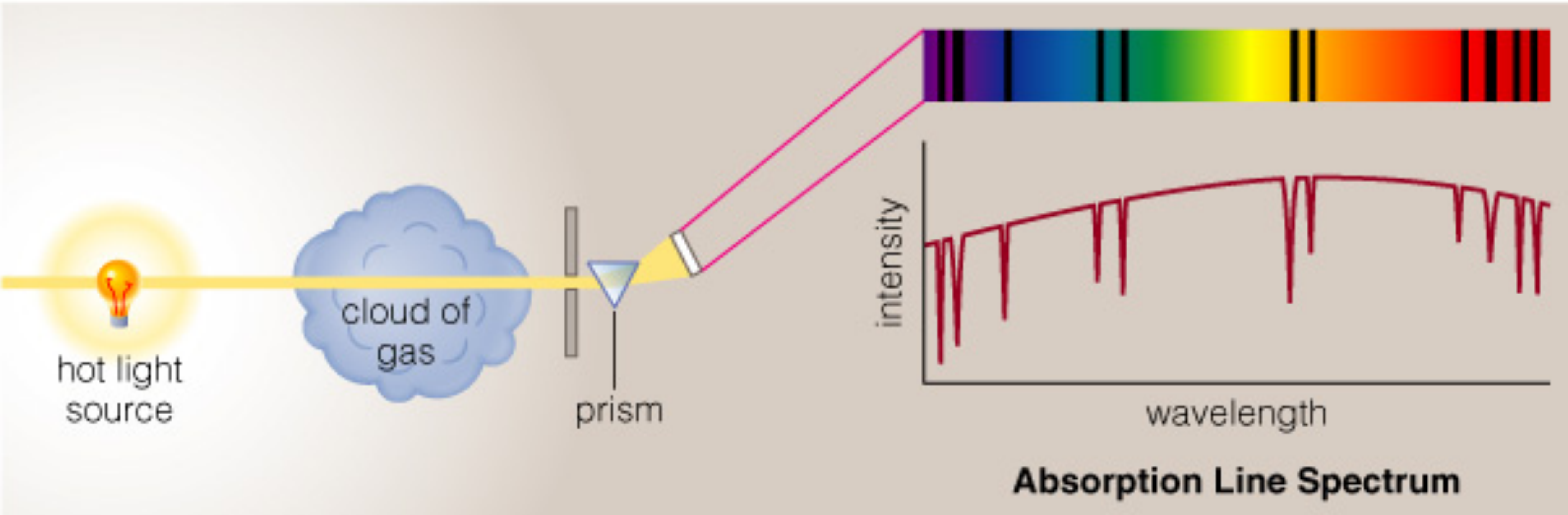
- Example: The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption. (star's interior)
- A hot solid, liquid or dense gas produces a continuous thermal spectrum (Kirchhof's 1st Law)

Emission Line Spectrum



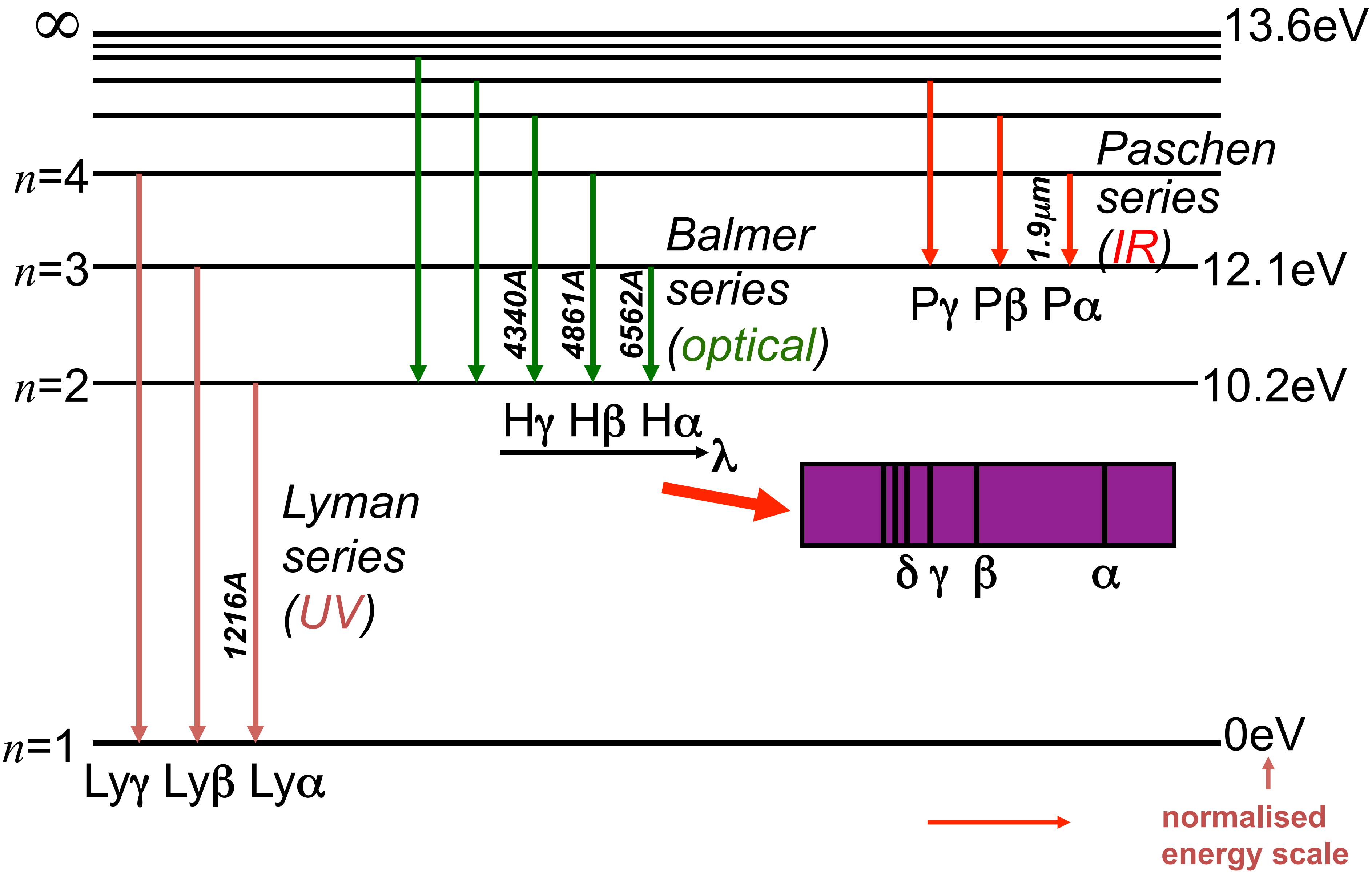
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines (Kirchhof' s 2nd Law).

Absorption Line Spectrum



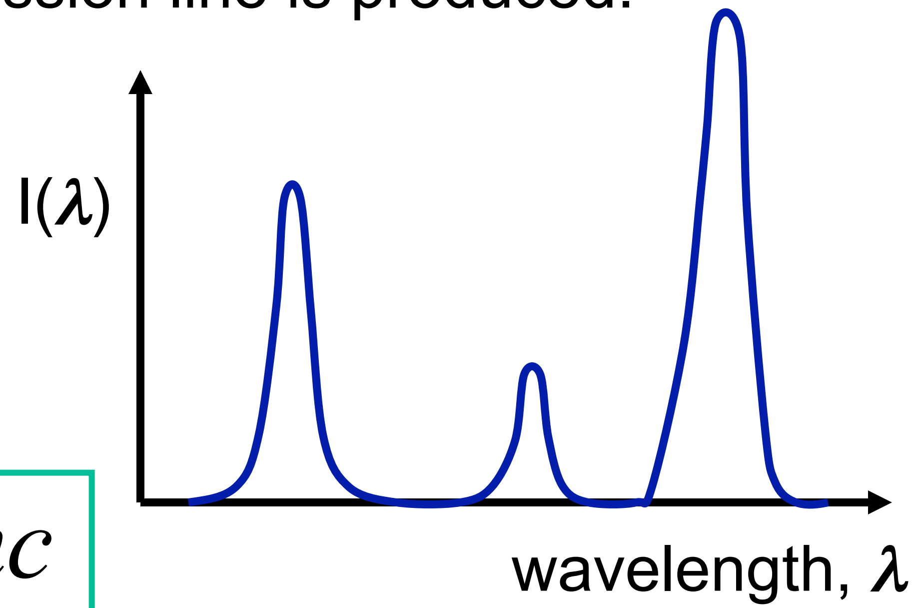
- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum: Kirchhof's 3rd Law

Spectrum of the hydrogen atom



Emission lines

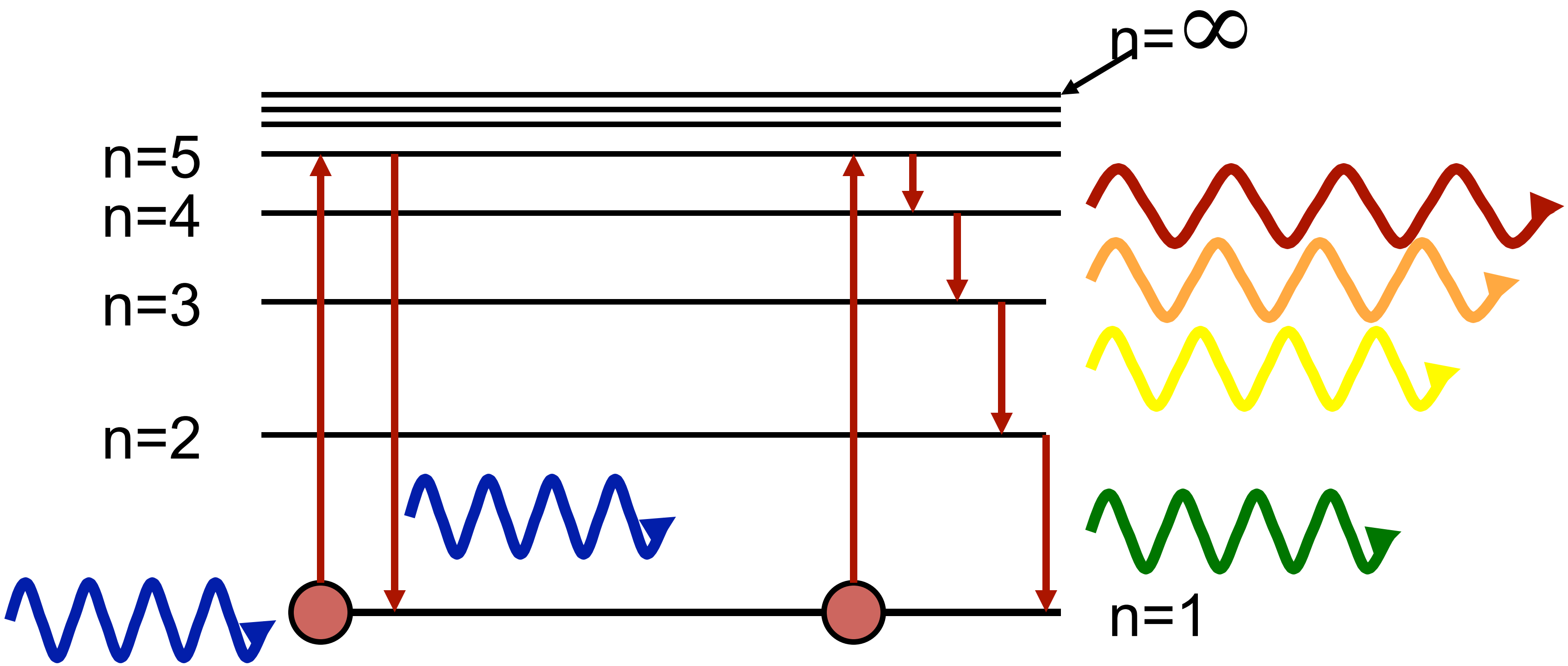
To produce emission lines, an excited state must first be populated – when the electron in an excited state falls by one or more levels, an emission line is produced.



..

$$\boxed{\Delta E = h\nu} \Rightarrow \boxed{\lambda = \frac{hc}{\Delta E}}$$

e.g. Photo-excitation



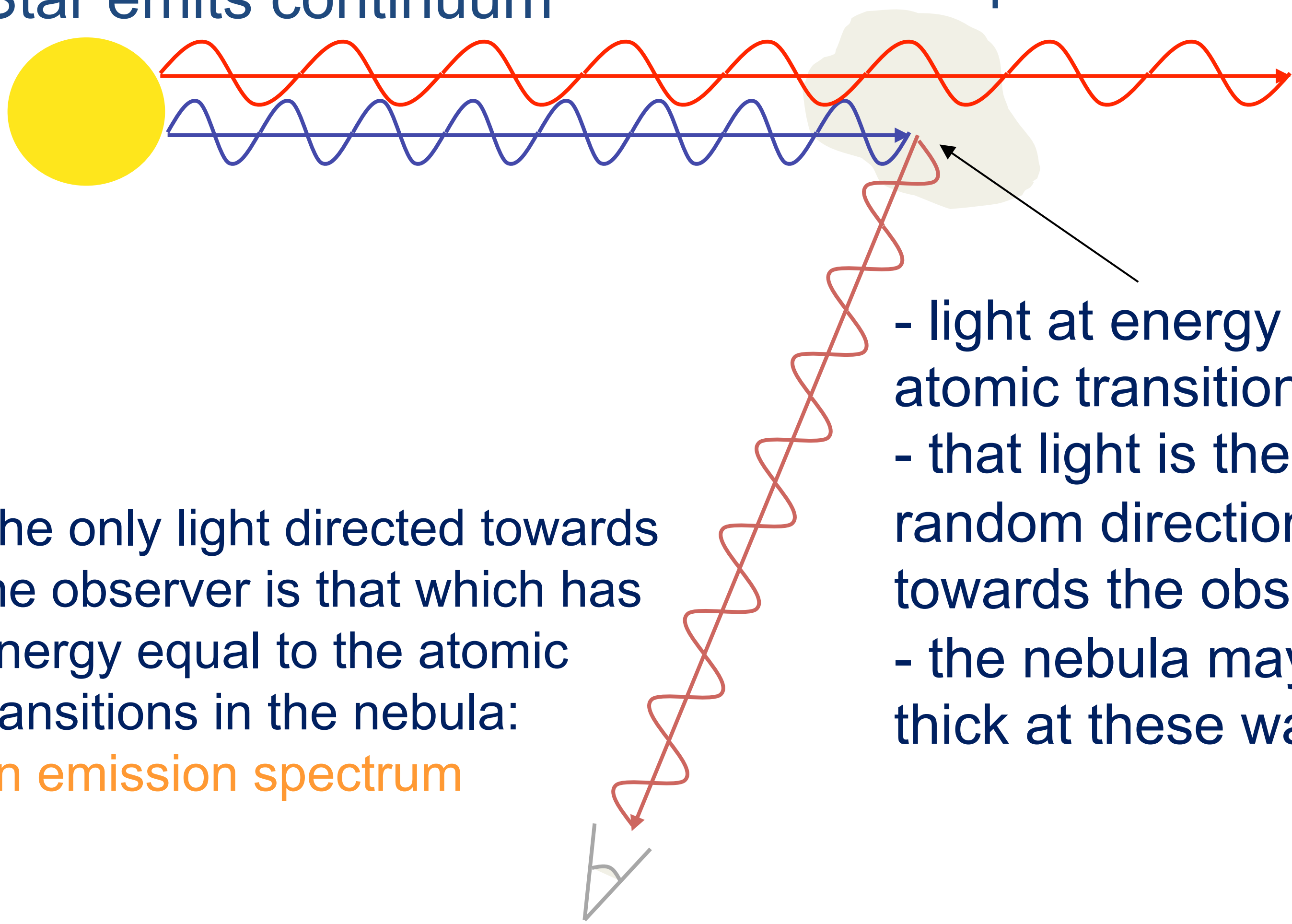
If a photon with the right energy interacts with an atom or ion, an electron can be moved up to a higher level for a short while, before it falls back down to the ground state.

Emission Nebula

(photo-excited or photo-ionized)

optically thin nebula:
passes most wavelengths

Star emits continuum

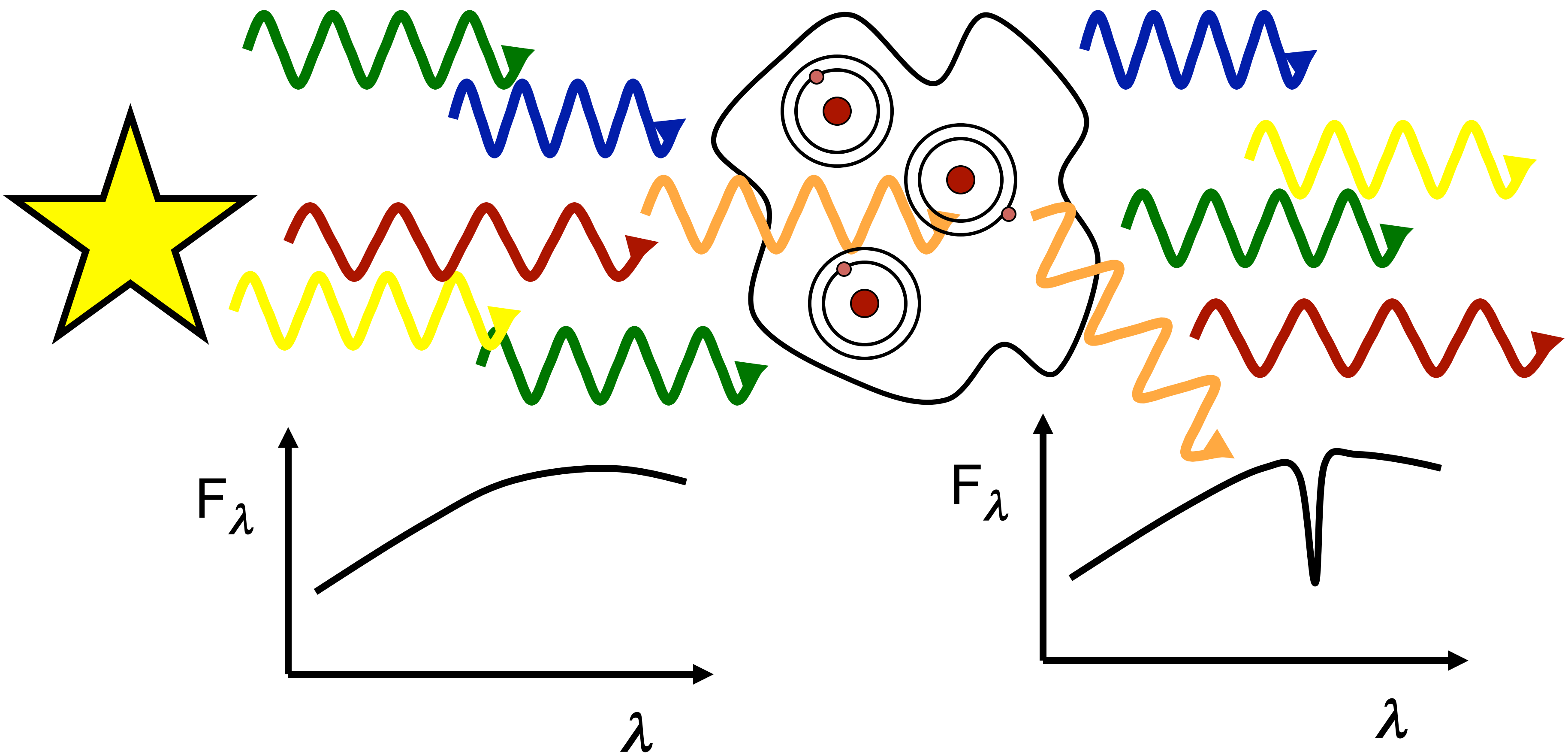


- light at energy equal to an atomic transition is absorbed
- that light is then reemitted in a random direction (some of it towards the observer)
- the nebula may be optically thick at these wavelengths

The only light directed towards the observer is that which has energy equal to the atomic transitions in the nebula:
an emission spectrum

Absorption lines formation

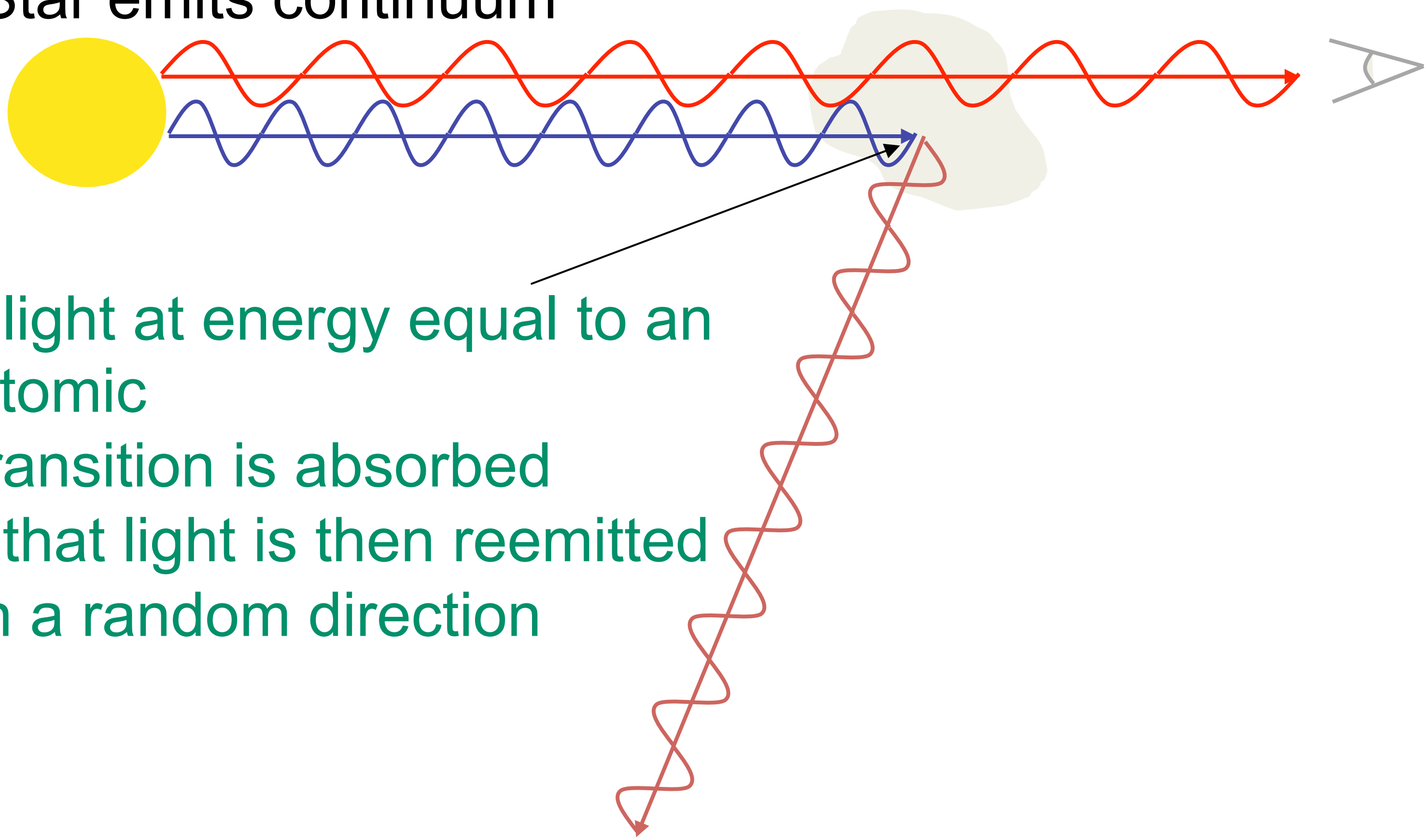
When atoms/ions in a gas are illuminated, they will absorb photons at those wavelengths which will move electrons in the atoms/ions from one level to another.



Absorption Feature:

the observer sees all the
wavelengths except those
at the atomic transition energy
an absorption spectrum

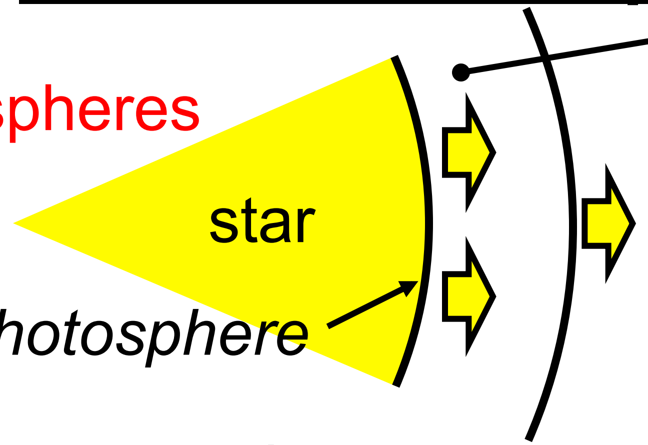
Star emits continuum

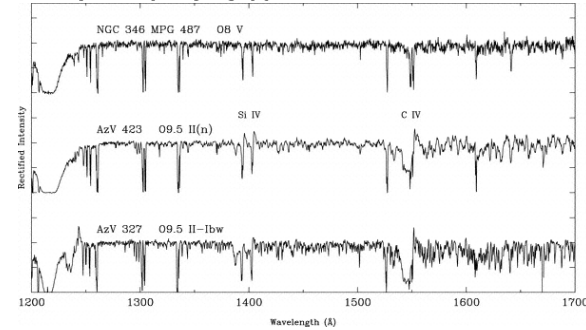


- light at energy equal to an
atomic
transition is absorbed
- that light is then reemitted
in a random direction

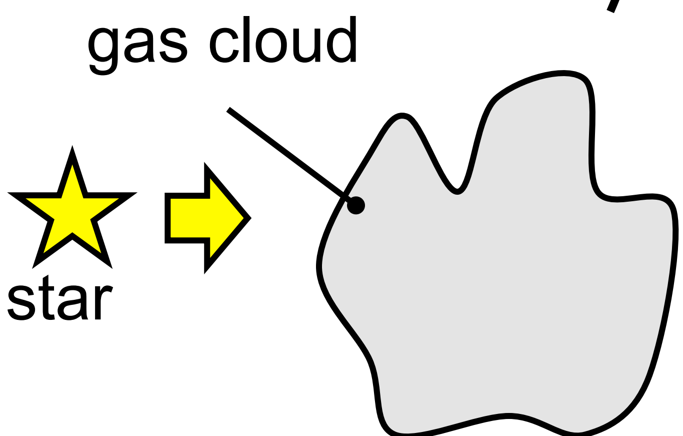
(INSERT) *Sources of absorption lines*

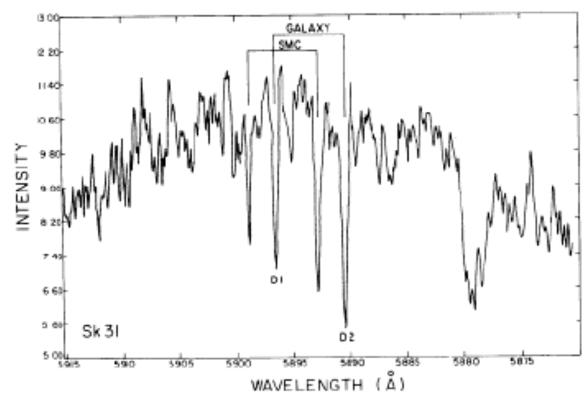
Stellar atmospheres



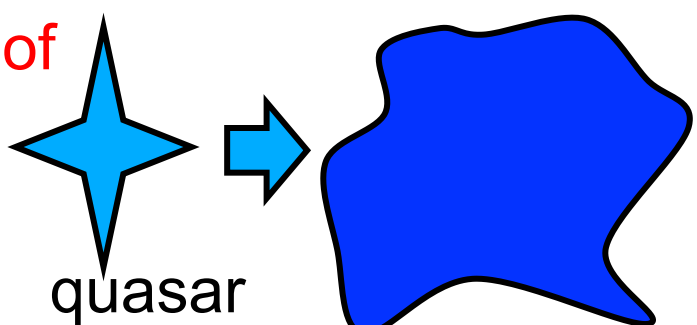


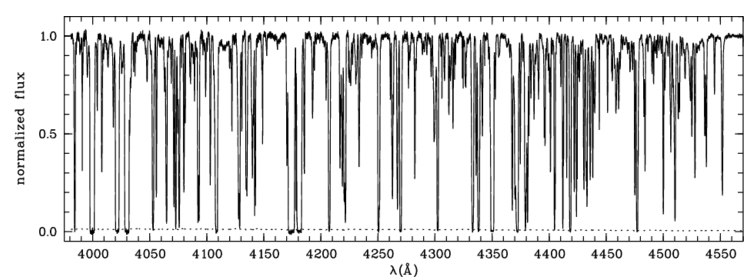
Interstellar gas





Intergalactic Lyα systems of clouds at different redshifts





'Lyα forest'

Doppler effect

The **Doppler effect** is of fundamental importance in astrophysics.

The observed wavelength, λ, is different from the emitted wavelength, λ_0, due to the radial velocity of the emitter with respect to the observer:

$$\boxed{\frac{(\lambda - \lambda_0)}{\lambda_0} \equiv \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}}$$

λ = observed wavelength

λ_0 = 'rest' wavelength

v = source's radial velocity

$\lambda > \lambda_0$ implies a 'redshift' of the light, $v > 0$, the emitter is moving away from the observer

$\lambda < \lambda_0$ implies a 'blueshift' of the light, $v < 0$, the emitter is moving towards the observer

'Astronomical redshift' $\boxed{z \sim \frac{v}{c}}$ when $z << 1$

Stellar classification

A star is a hot, dense ball of gas. It emits approximately a blackbody spectrum at a single temperature from its photosphere (lowest visible layers).

From Wien's law: Hotter a star is, the bluer. Cool stars look red and intermediate temperature stars appear yellow.

Photosphere is surrounded by thin, warm atmosphere which imprints absorption lines on the continuum.

Which ions do the absorption depends on the temperature of the gas they are in …

Classification of Stars

→From 1910, adopted Harvard (or **Henry Draper; HD**) spectral classification system

- Based on spectral characteristics
- This gives information about temperature in an alternative way
- Absorption lines can be observed only for a certain range of temperatures
- The range involved shows atomic energy levels which have been populated

The Harvard classification

O B A F G K M L T

emission absorption

H

II ← He → I II ← metals → I

III ← O,N → II molecules

	blue-white	white	yellow	red		
Teff [K]	30000	10000	5000	3000	2000	~700

Divisions and subdivisions

- …later …. discovered that the strength of the hydrogen line was connected with the surface temperature of the star.
- These classes are further subdivided by numbers (0-9)
- A0 denotes the hottest stars in the A class and A9 denotes the coolest ones
- The sun is classified as G2.

Stellar spectral types

Spectral class	Colour	Surface temp (K)	Main lines	Example
O	Blue-violet	30000-50000	He II	Naos
B	Blue-white	11000-30000	He I	Rigel, Spica
A	White	7500-11000	H, Fe II, Si II, Mg II	Sirius, Vega
F	Yellow-white	6000-7500	Ca II	Canopus, Procyon
G	Yellow	5000-6000	Ca II, Fe I, CH	Sun, Capella
K	Orange	4000-5000	Ca II, Fe I	Arcturus, Aldebaran
M	Red-orange	<4000	Fe I, TiO	Betelgeuse, Antares

thus two-dimensional…..

- Difference in stars is not just their chemical make up but their surface temperature AND size
- Spectra of two stars with same temperature but different sizes is not the same
- + larger star will have higher luminosity

Stellar spectral types (5)

1943: Morgan & Keenan added **luminosity** as a second classification parameter ➔ 2-d scheme

Luminosity classes are designated by the Roman numerals I →V, in order of decreasing luminosity:

Ia = Most luminous supergiants
Ib = Supergiants
II = Luminous giants
III = Giants
IV = Subgiants
V = Main sequence stars (dwarfs)

The Sun is a **G2V** star and has an effective (surface) temperature of ~6000 K.

Hertzsprung-Russell diagrams

1911-1913: Hertzsprung and Russell independently plotted stellar luminosity vs temperature (or spectral type).

Stars populate the diagram preferentially in certain regions. This may be partially understood in terms of luminosity of an object emitting thermal radiation:

$$L \sim R^2 T^4$$

H-R diagram for nearby+bright stars:

All stars visible to the naked eye + all stars within 25 pc