Ay 122 - Fall 2004

Electromagnetic Radiation And Its Interactions With Matter

(This version has many of the figures missing, in order to keep the pdf file reasonably small)

Radiation Processes: An Overview

- Physical processes of electromagnetic radiation (EMR) emission and absorption
  - Kirchoff's laws
  - Discrete (quantum) processes
  - Continuum processes
- Next time: radiation transfer, spectral lines, stellar atmospheres and spectral types

(Many slides today from P. Armitage)

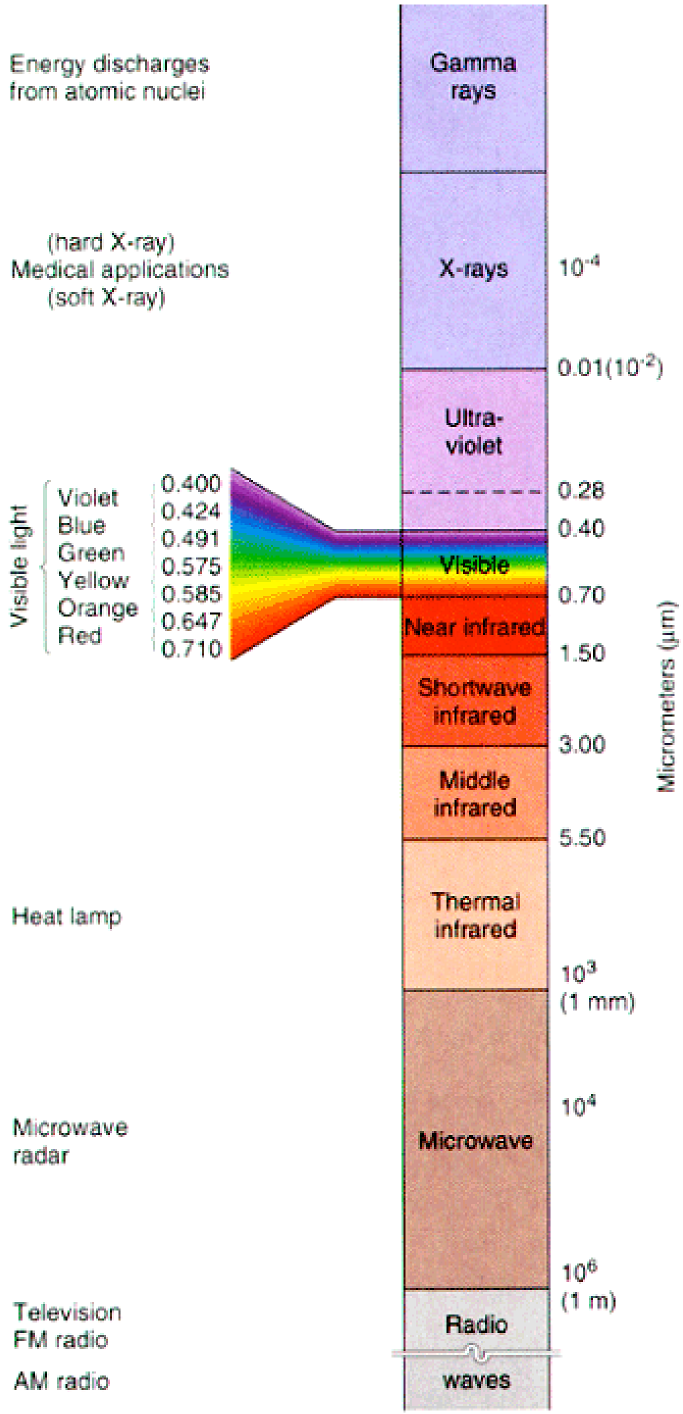
Primary Astrophysical Processes Emitting Radio Radiation

When charged particles change direction (i.e., they are accelerated), they emit radiation

EMR
- Discrete (quantum transitions)
- Continuum
  - Thermal (i.e., blackbody)
  - Nonthermal:
    - Synchrotron
    - Free-free
    - Cherenkov

Which one(s) will dominate,
depends on the physical conditions of the gas/plasma.
Thus, EMR is a *physical diagnostic*.

Different Physical Processes Dominate at Different Wavelengths



source: Christopherson (2000) *Geosystems*

Nuclear energy levels

Inner shells of heavier elements

Atomic energy levels (outer shells)

Molecular transitions

Hyperfine transitions

Plasma in typical magnetic fields

Kirchoff's Laws

1. **CONTINUOUS SPECTRUM**: Any hot opaque body (e.g., hot gas/plasma) produces a continuous spectrum or complete rainbow
2. **EMISSION SPECTRUM**: A hot transparent gas will produce an emission line spectrum
3. **ABSORPTION SPECTRUM**: A (relatively) cool transparent gas in front of a source of a continuous spectrum will produce an absorption line spectrum

Modern atomic/quantum physics provides a ready explanation for these empirical rules

Kirchoff's Laws in Action:

Laboratory spectra ➔ Line identifications in astro.sources
Analysis of spectra ➔ Chemical abundances + physical conditions (temperature, pressure, gravity, ionizing flux, magnetic fields, etc.)
+ Velocities

Atomic Processes

Radiation can be emitted or absorbed when electrons make transitions between different states:

Bound-bound: electron moves between two bound states (orbitals) in an atom or ion. Photon is emitted or absorbed.

Bound-free:

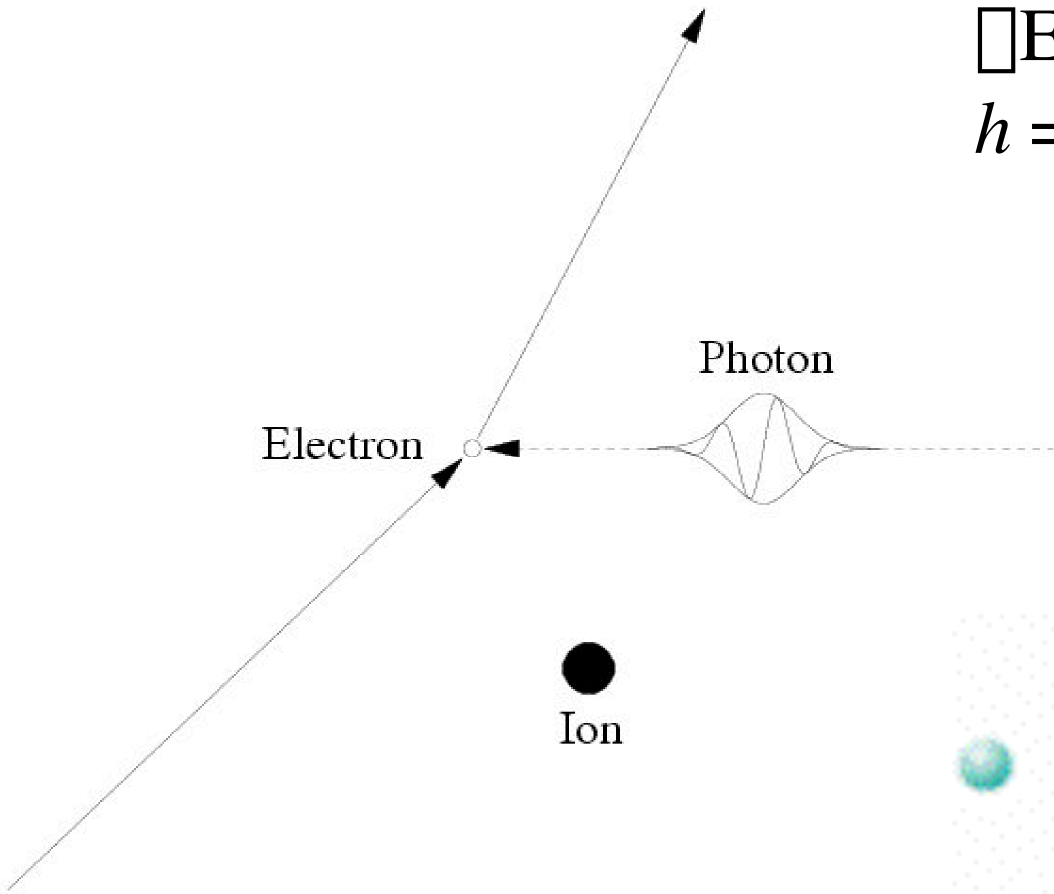
- Bound -> unbound: **ionization**
- Unbound -> bound: **recombination**

Free-free: free electron gains energy by absorbing a photon as it passes near an ion, or loses energy by emitting a photon. Also called **bremsstrahlung**.

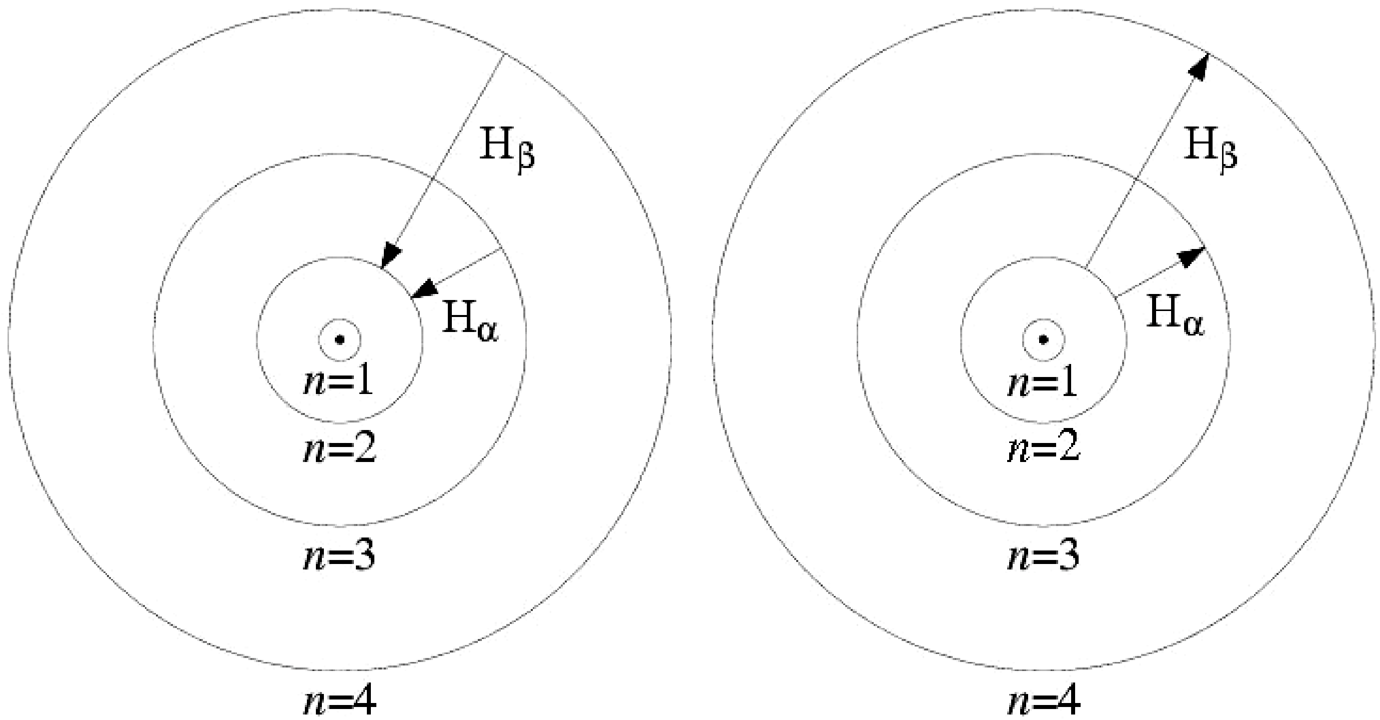
Energy Transitions: Free-Free

$\Delta E(e^-) = E(\gamma) = h\nu = hc/\lambda$

h = Planck's constant



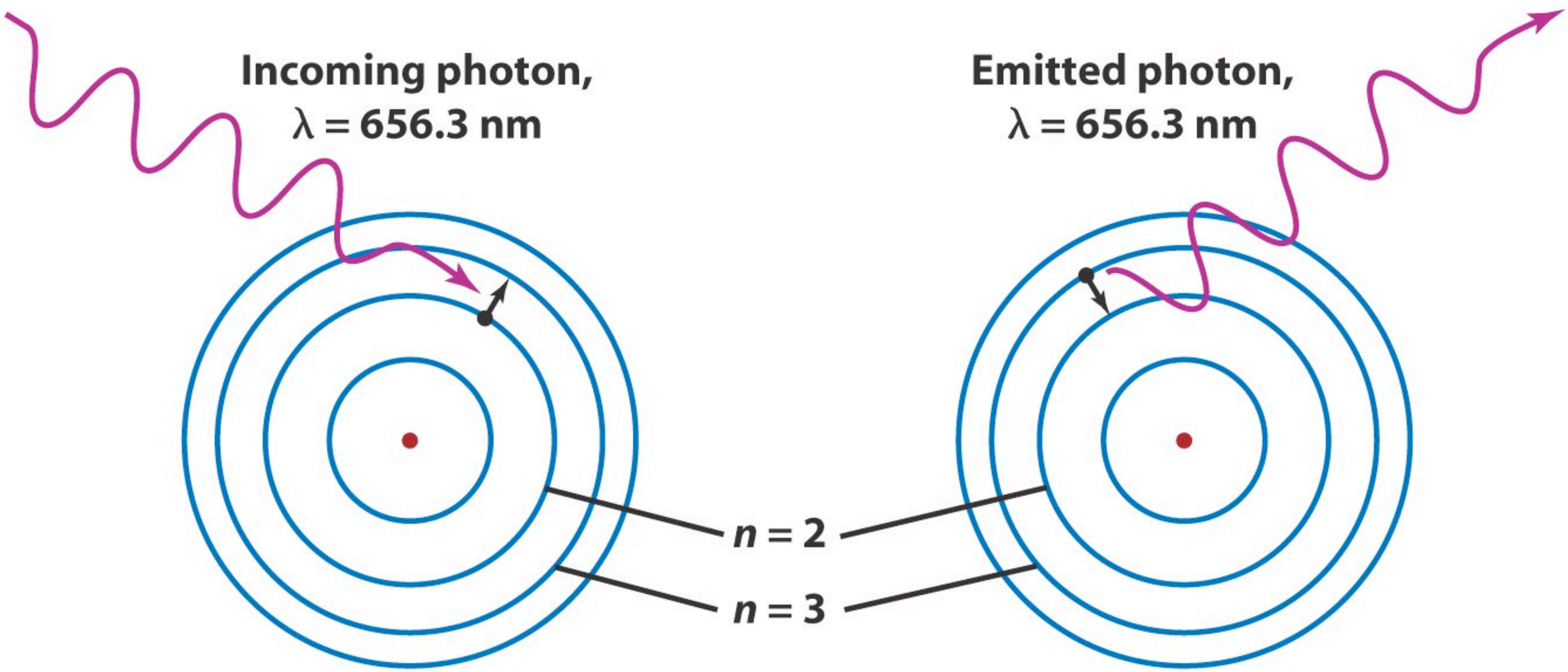
Energy Transitions: The Bohr Atom



Atoms transition from lower to higher energy levels (**excitation / de-excitation**) in discrete quantum jumps. The energy exchange can be **radiative** (involving a photon) or **collisional** (2 atoms)

Example of an Atomic Energy Transition: Hydrogen Atom

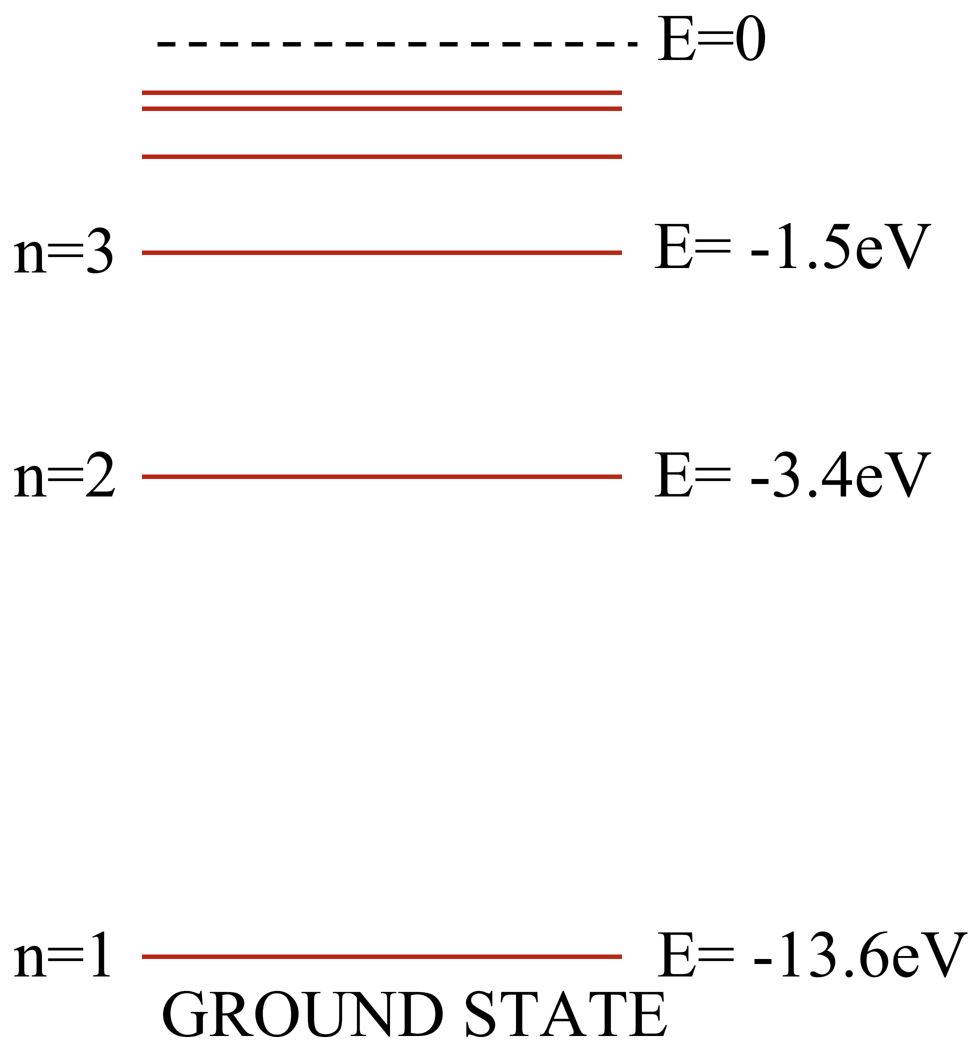
Photon energy: $h\nu = |E_i - E_j|$



(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up to the $n = 3$ orbit

(b) Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon

Hydrogen Energy Levels



Energy levels are labeled by n - the *principal Quantum number.*

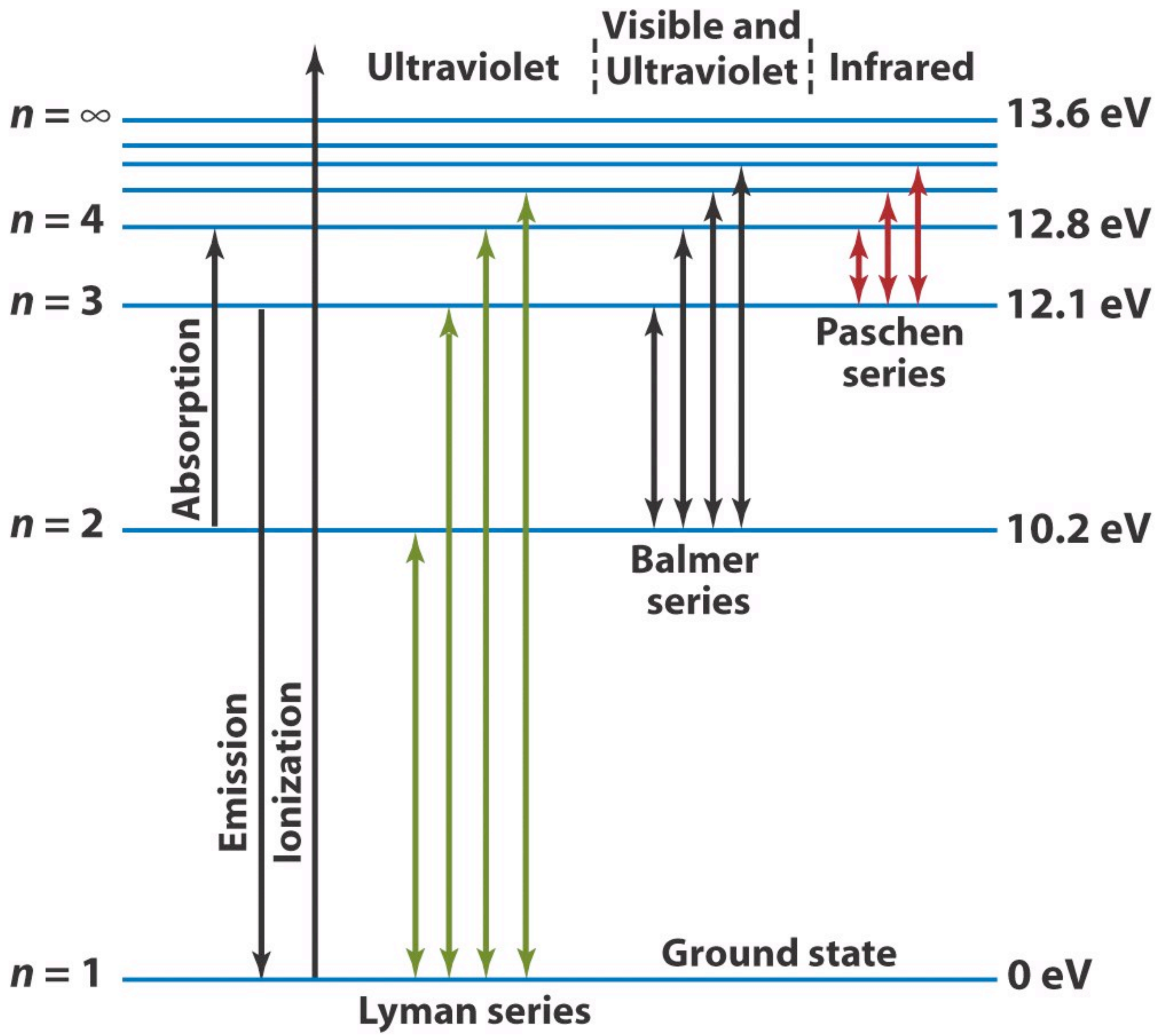
Lowest level, n=1, is the ground state.

$$E_n = -\frac{R}{n^2}$$

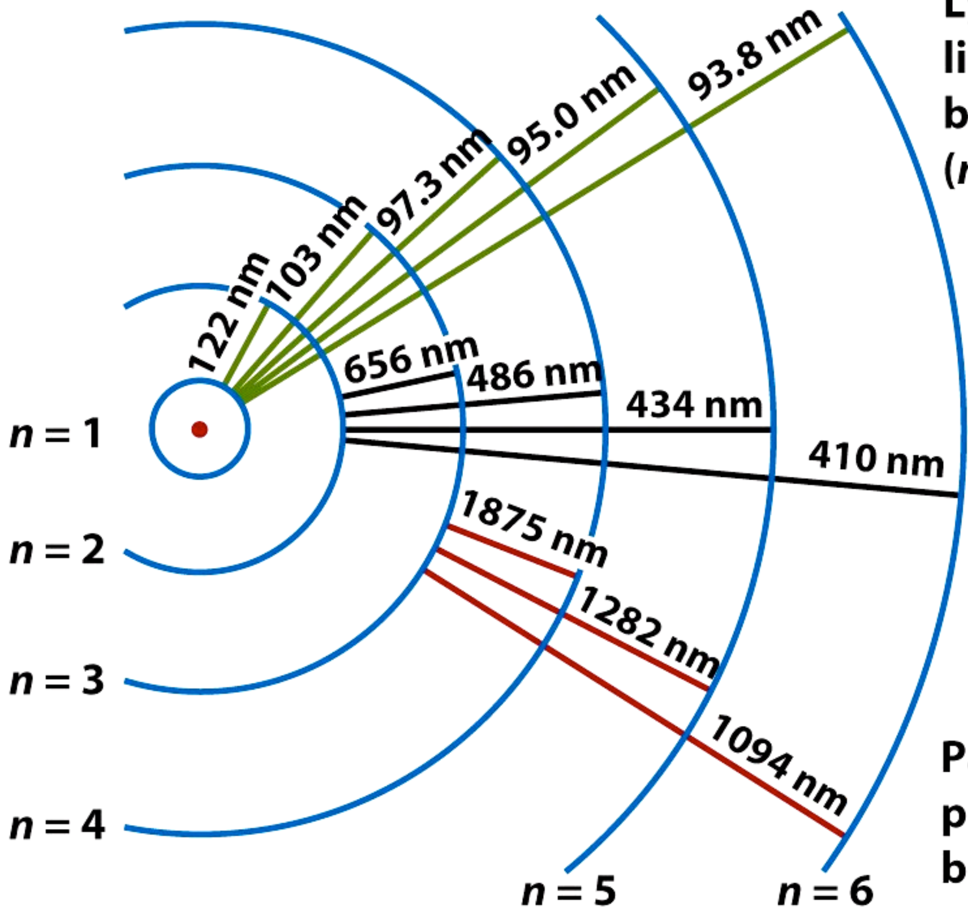
where R = 13.6 eV is a Constant (Rydberg)

n-th energy level has $2n^2$ quantum states, which are degenerate (same E).

Energy Levels in a Hydrogen Atom



Families of Energy Level Transitions Correspond to Spectroscopic Line Series

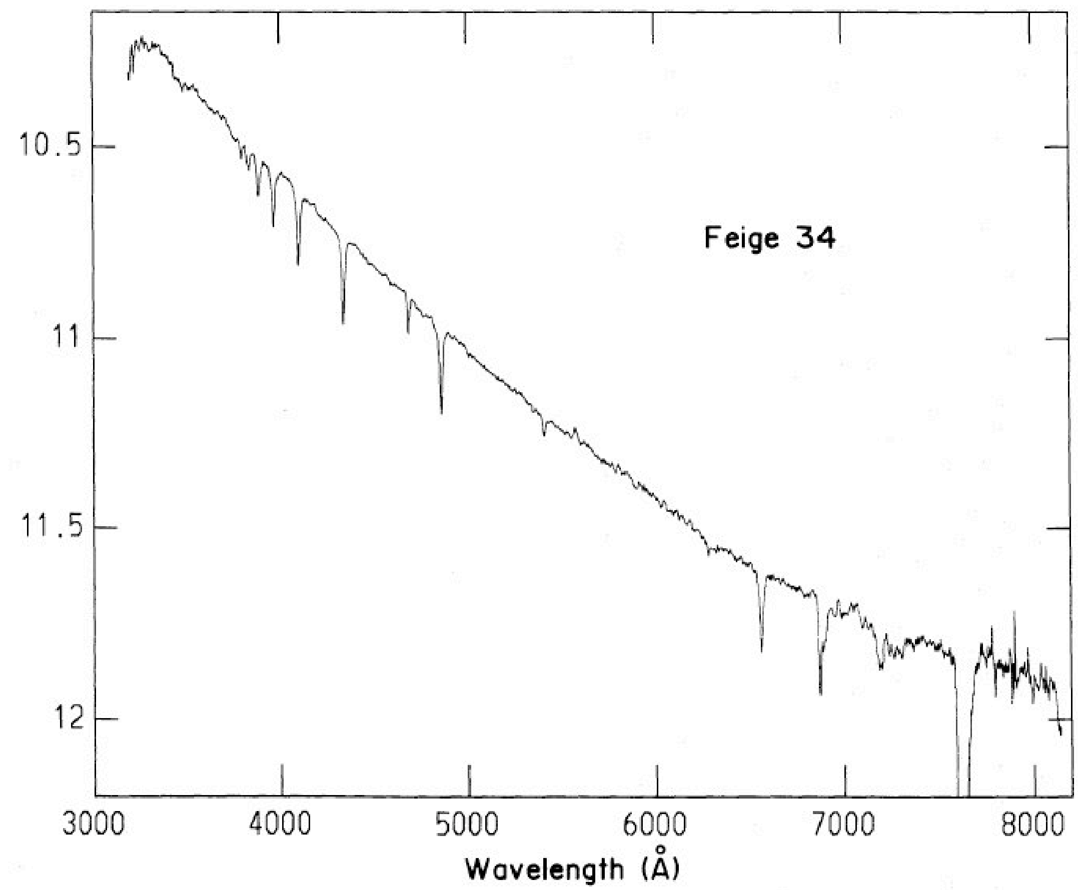


Lyman series (ultraviolet) of spectral lines: produced by electron transitions between the *n* = 1 orbit and higher orbits (*n* = 2, 3, 4, ...)

Balmer series (visible and ultraviolet) of spectral lines: produced by electron transitions between the *n* = 2 orbit and higher orbits (*n* = 3, 4, 5, ...)

Paschen series (infared) of spectral lines: produced by electron transitions between the *n* = 3 orbit and higher orbits (*n* = 4, 5, 6, ...)

Balmer Series Lines in Stellar Spectra



Which Energy Levels and Transitions?

Even for H - simplest atom - huge number of pairs of energy levels with different DE and hence different *n*. How do we decide which lines we will see?

• At particular T, some levels will have a higher probability of being occupied than others.

• Probability of some transitions is greater than others.

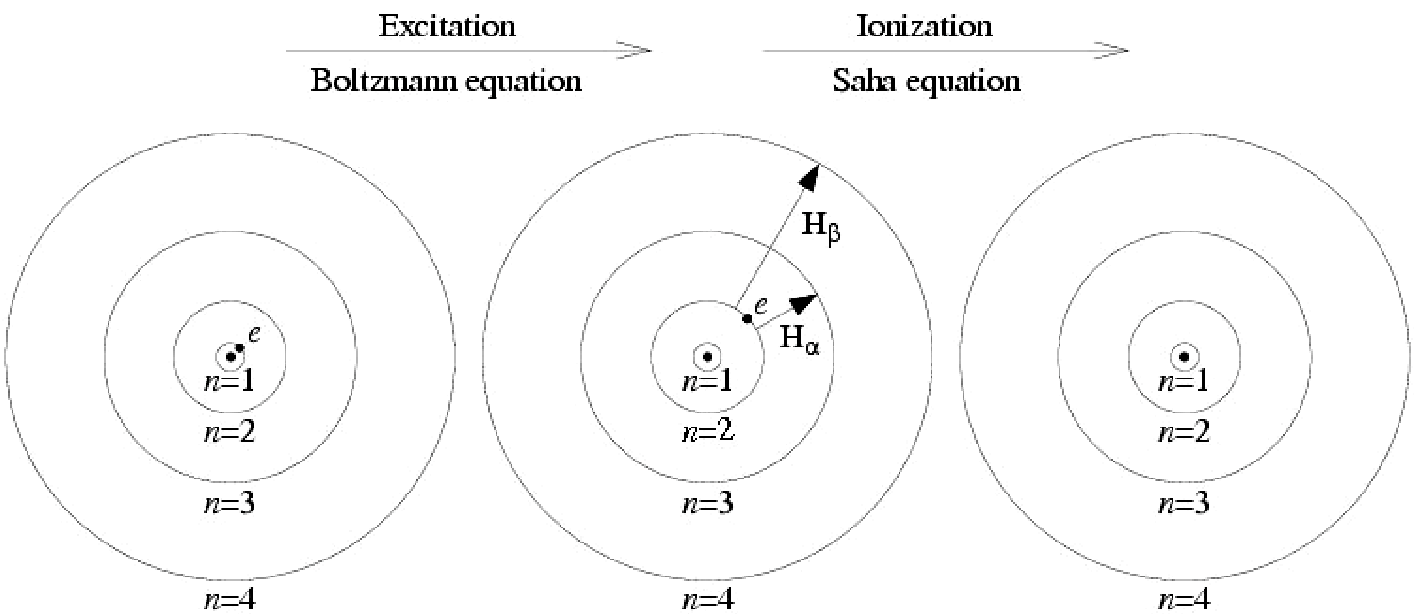
• Not all transitions are possible (*selection rules*).

↓

Because of conservation laws - e.g. since a photon carries angular momentum cannot make a transition between two states with zero angular momentum by emitting one photon.

Computing the Occupation of Energy Levels

… from which we can then compute the relative intensities of spectroscopic lines



Need gas [□,T] and radiation spectrum and intensity (or just T_e, if it's a thermal spectrum). The key question is whether the gas and the radiation field are in a *thermal equilibrium*

Boltzmann's Law

Calculating the populations of energy levels is difficult if The gas is not in local thermodynamic equilibrium (LTE). In LTE, it is very easy. At temperature T, populations n_1 and n_2 of any two energy levels are:

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-(E_2 - E_1)/kT}$$

g_1 and g_2 are the statistical weights of the two levels (allow for the fact that some energy levels are degenerate). For hydrogen:

$$g_n = 2n^2$$

Emission or Absorption?

It depends on whether the gas (plasma) is

Optically thick: short mean free path of photons, get absorbed and re-emitted many times, only the radiation near the surface escapes; or

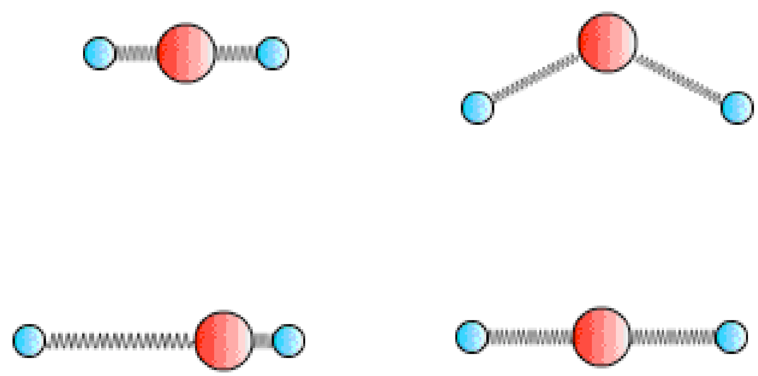
Optically thin: most photons escape without being reabsorbed or scattered

(Note that a medium can be optically thick or thin for either line or continuum photons. Optical thickness is generally proportional to density.)

And then it depends on the **geometry:** if a continuum is seen though a cooler, optically thin gas, you will see an absorption spectrum; but if the gas is hotter, there will be an emission line spectrum superposed on the cont.

Spectral Line Emission: Molecular Rotational and Vibrational Modes

These transitions (or energy splittings) have generally lower energies (thus prominent in IR/sub-mm), but many more levels (thus complex spectra)

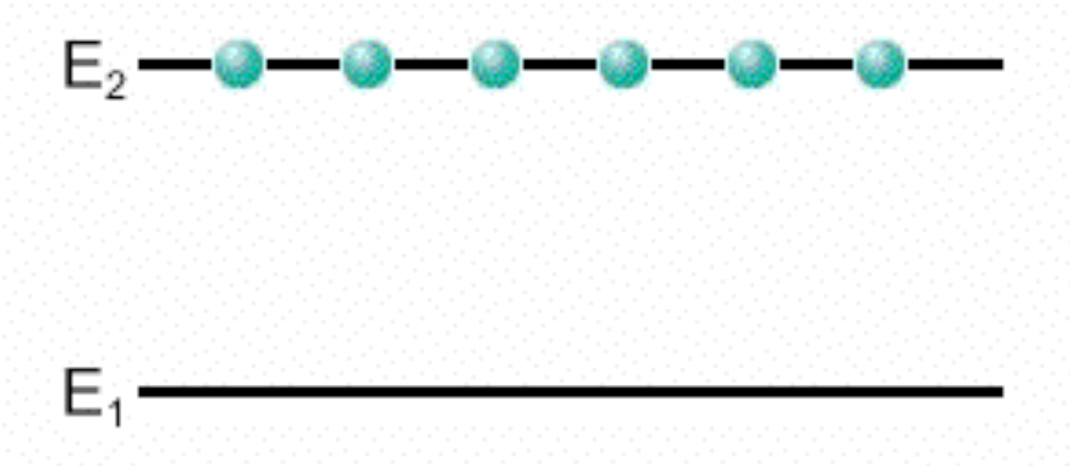


Example:
Orion
spectrum
from CSO

Astrophysical Molecular Spectroscopy

- Because of the lower energy levels of molecular transitions, they are a good probe of colder gas (T ~ 10 - 100 K), e.g., star forming regions
- Commonly observed molecules in space include: hydrogen (H_2) carbon monoxide (CO), water (H_2O), OH, HCN, HCO^+, CS, NH_3, formaldehyde (H_2CO), etc. Less common molecules include sugar, alcohol, antifreeze (ethylene glycol), …
- As a bonus, longer wavelengths are not affected much by the interstellar extinction

Maser Emission



- Stimulated emission from overpopulated energy levels
- Sometimes seen in star-forming regions, or cold stellar envelopes
- Produces very sharp emission lines - an excellent tracer of velocity fields (e.g., for central massive black holes)

Hydrogen 21cm Line

Ground state of hydrogen (n=1) has $2 \times 1^2 = 2$ states.

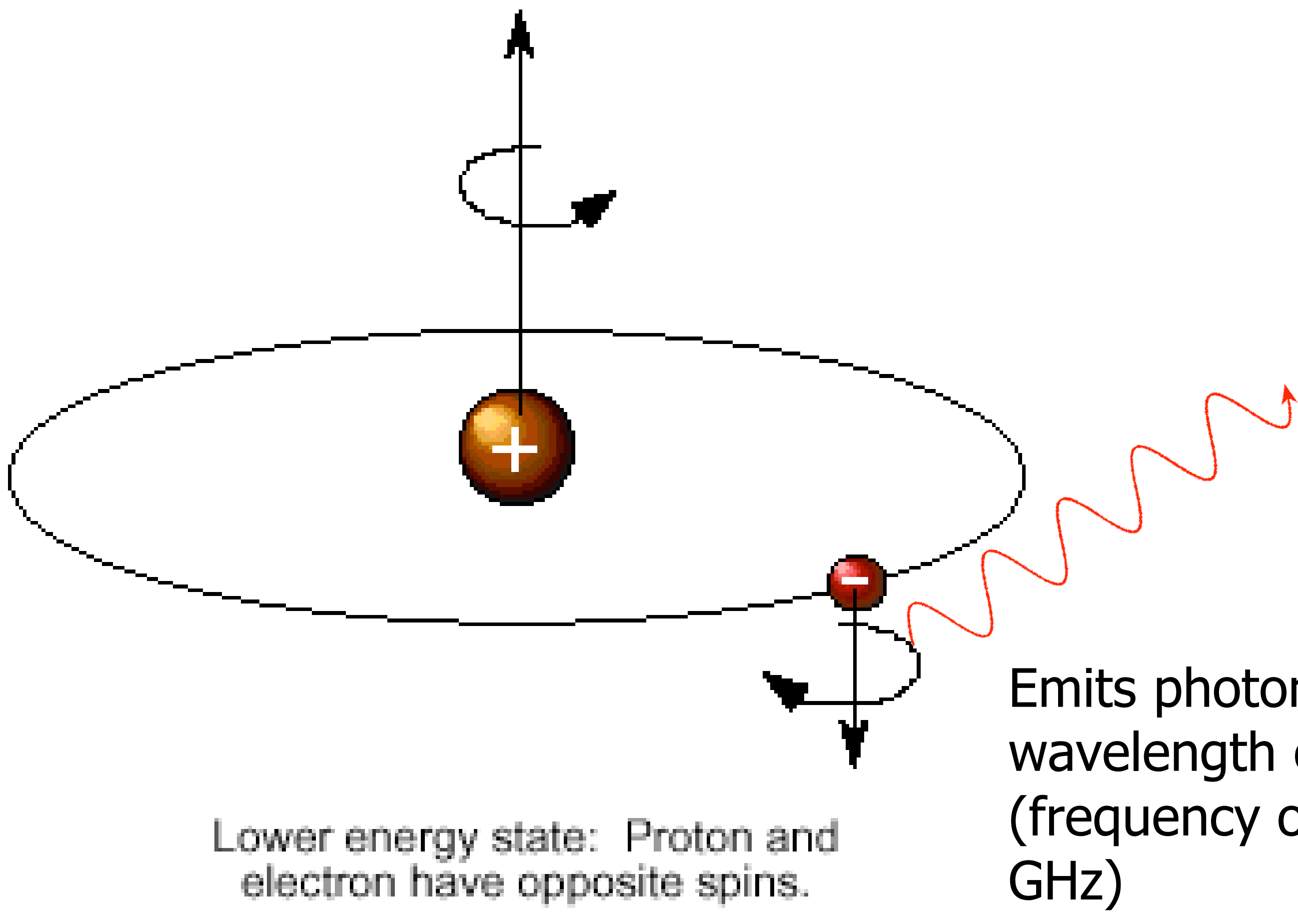
Correspond to different orientations of the electron spin relative to the proton spin.

Very slightly different energies - *hyperfine splitting*.

Energy difference corresponds to a frequency of 1.42 GHz, or 21cm wavelength.

Very important for radio astronomy, because neutral hydrogen is so abundant in the Universe. This is the principal wavelength for studies of ISM in galaxies, and their disk structure and rotation curves.

Spectral Line Emission: Hyperfine Transition of Neutral Hydrogen



Emits photon with a wavelength of 21 cm (frequency of 1.42 GHz)

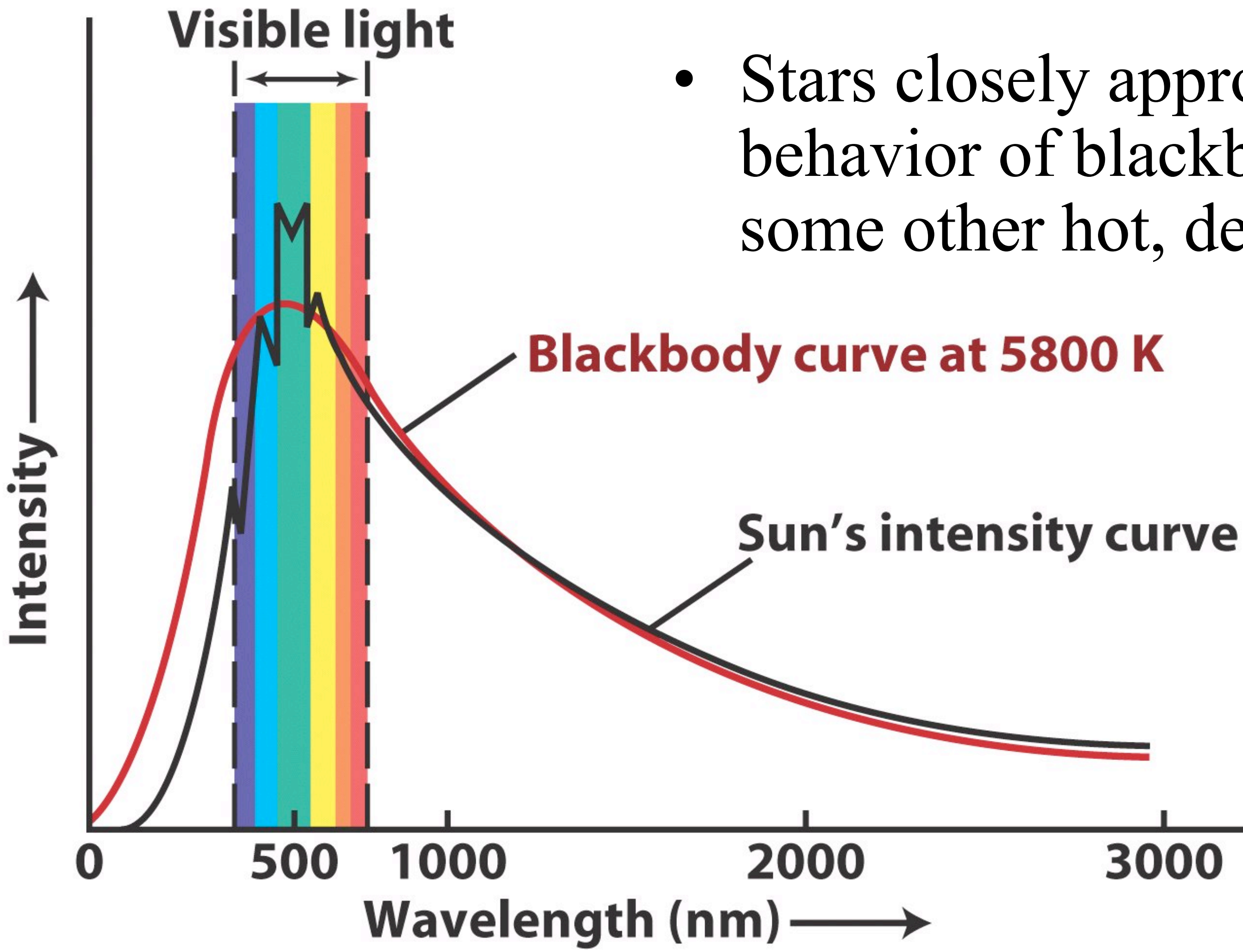
Transition probability=3×10^{-15} s^{-1} = once in 11 Myr

Thermal Continuum Emission

- **Blackbody** emission from warm bodies
  - Planck formula
  - Optically thick medium
- **Bremsstrahlung** or free-free emission from ionized plasmas, from accelerating charged particles
  - Optically thin medium

Blackbody Radiation

- A blackbody is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths

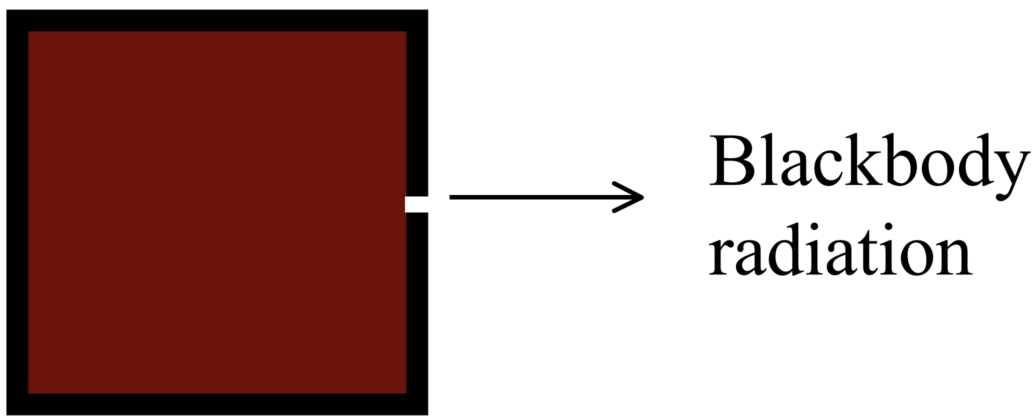


- Stars closely approximate the behavior of blackbodies, as do some other hot, dense objects

Blackbody Radiation

This is radiation that is in ***thermal equilibrium*** with matter at some temperature T.

Lab source of blackbody radiation: hot oven with a small hole which does not disturb thermal equilibrium inside:



Important because:

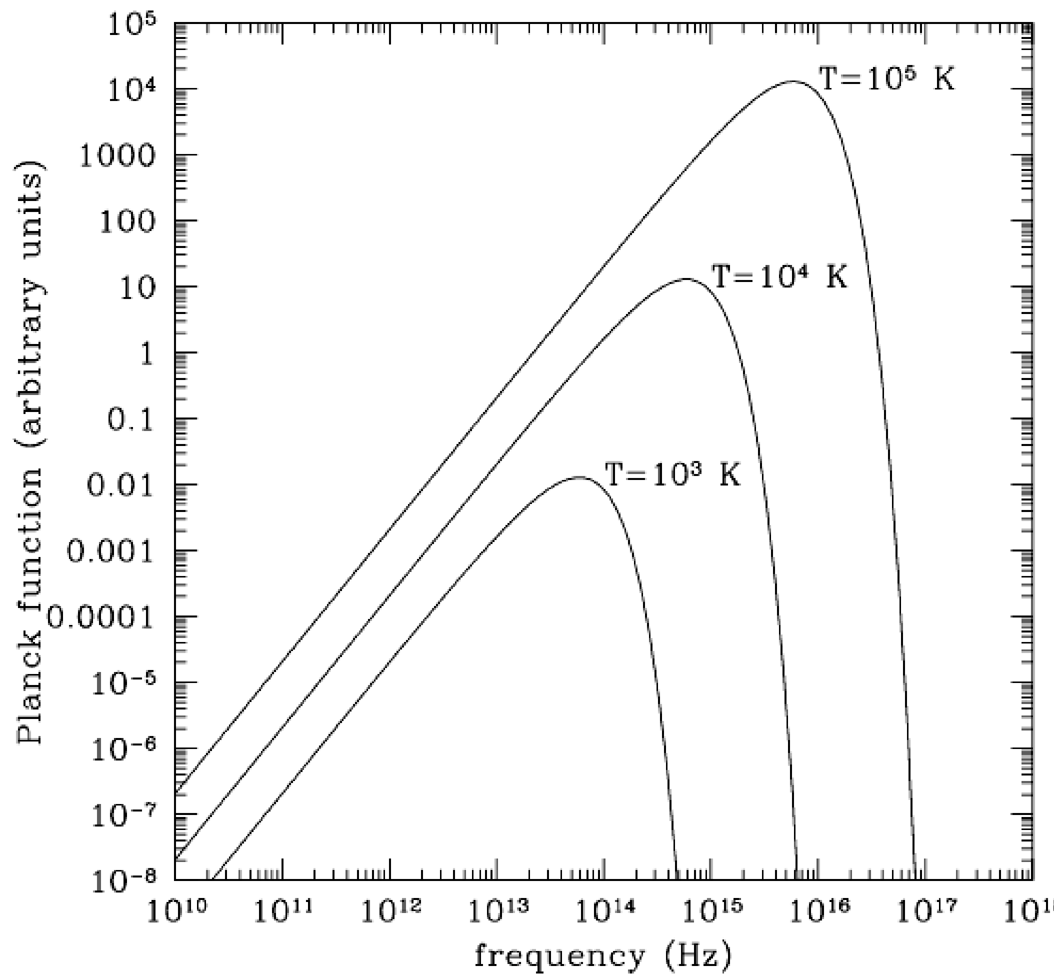
- Interiors of stars (for example) are like this
- Emission from many objects is roughly of this form.

Blackbody Spectrum

The frequency dependence is given by the **Planck function**:

$$B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}$$

h = Planck's constant
k = Boltzmann's constant



Same units as specific intensity: erg s^{-1} cm^{-2} $sterad^{-1}$ Hz^{-1}

Blackbody Spectrum

The Planck function peaks when $dB_\nu(T)/d\nu = 0$:

$$h\nu_{\mathrm{max}} = 2.82kT$$

$$\nu_{\mathrm{max}} = 5.88 \times 10^{10}\, T \text{ Hz K}^{-1}$$

This is ***Wien displacement law*** - peak shifts linearly with Increasing temperature to higher frequency.

Asymptotically, for low frequencies $h\nu \ll kT$, the ***Rayleigh-Jeans law*** applies:

$$B_\nu^{RJ}(T) = \frac{2\nu^2}{c^2} kT$$

Often valid in the radio part of the spectrum, at freq’s far below the peak of the Planck function.

Black(body) Power!

The energy density of blackbody radiation:

$$u(T) = aT^4$$

$a = 7.56 \times 10^{-15}$ erg cm^{-3} K^{-4} is the radiation constant.

The emergent flux from a surface emitting blackbody radiation is:

$$F = \sigma T^4$$

$\sigma = 5.67 \times 10^{-5}$ erg cm^{-2} K^{-4} s^{-1} = Stefan-Boltzmann const.

A sphere (e.g., a star), with a radius R, temperature T, emitting as a blackbody, has a luminosity:

$$L = 4\pi R^2 \sigma T^4$$

Effective Temperature

Emission from most astronomical sources is only roughly described by the Planck function (if at all).

For a source with a bolometric flux ***F***, define the **effective temperature *T_e*** via:

$$F \equiv \sigma T_e^4$$

e.g., for the Sun: $L_{sun} = 4\pi R_{sun}^2 \sigma T_e^4$ …find $T_e = 5770$ K.

Note: effective temperature is well-defined even if the spectrum is nothing like a blackbody.

Big bang model - Universe was hot, dense, and in thermal equilibrium between matter and radiation in the past.

Relic radiation from this era is the **cosmic microwave background** radiation. Best known blackbody:

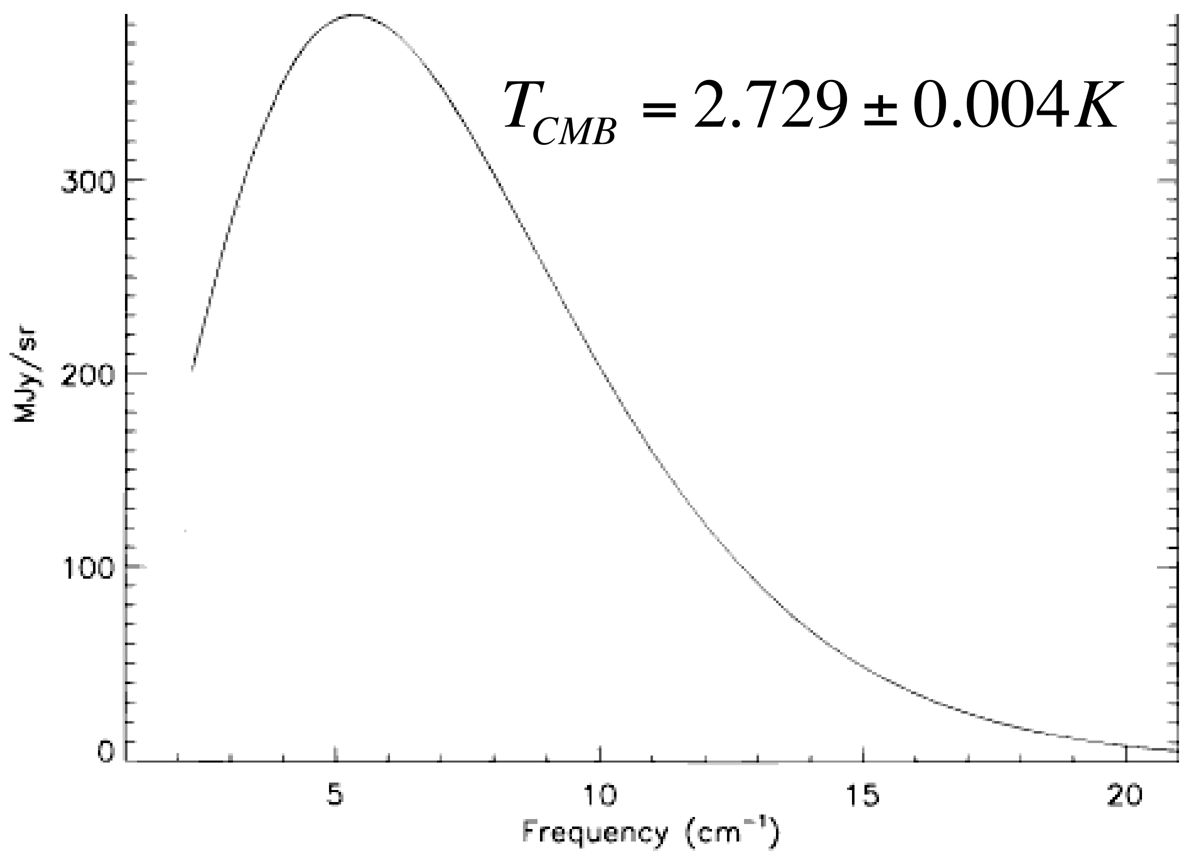


FIG. 4.—Uniform spectrum and fit to Planck blackbody (*T*). Uncertainties are a small fraction of the line thickness.

No known distortions of the CMB from a perfect blackbody!

Thermal Radiation Reprocessing: e.g., Planets

Two sources of radiation:

- Directly reflected Sun light
- Absorbed Solar radiation, reradiated as a blackbody

e.g. Jupiter: $L_{sun} = 3.86 \times 10^{33}$ erg s^{-1}

$a_J = 7.8 \times 10^{13}$ cm Jupiter orbital radius

$R_J = 7.1 \times 10^{9}$ cm Jupiter radius

Solar radiation incident on the planet is:

$$L_J = \frac{\pi R_J^2}{4\pi a_J^2} \times L_{sun} \approx 2 \times 10^{-9} L_{sun}$$

Suppose planet directly reflects 10% - in the optical Jupiter is $\sim 10^{10}$ times fainter than the Sun as seen from far away.

Thermal Radiation Reprocessing Example …

Absorb and reradiate as a blackbody:

$$L_J = 4\pi R_J^2 \cdot \sigma T_J^4$$

If all Sunlight is absorbed, estimate T = 120 K. Use:

$$h\nu_{max} = 2.82kT$$

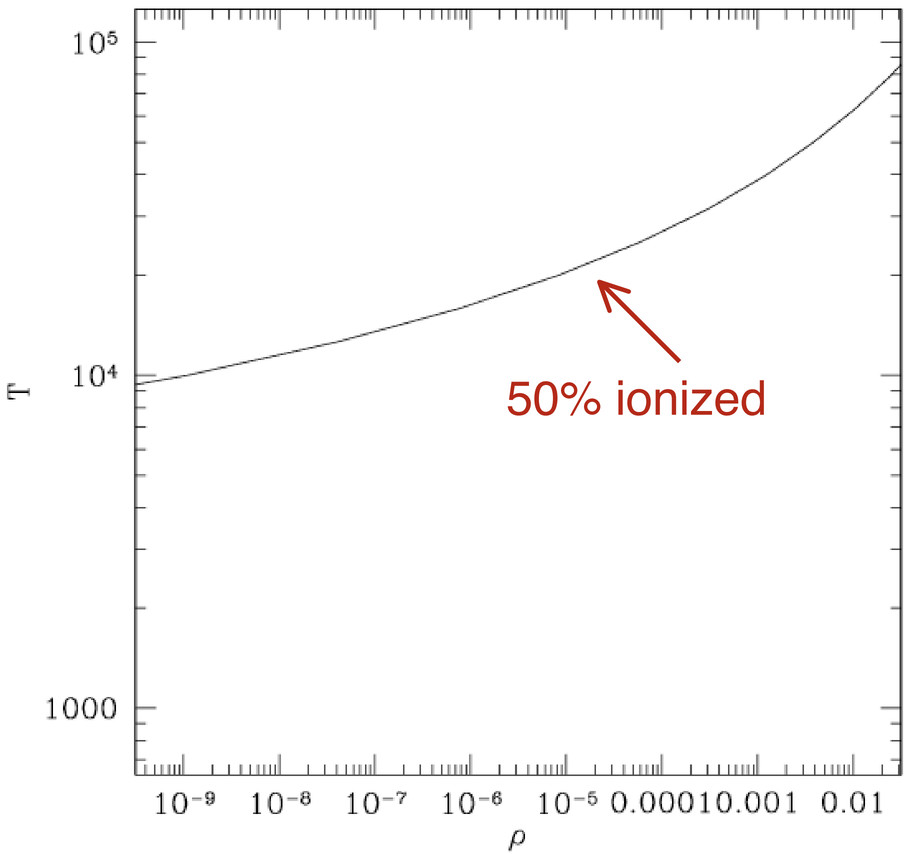
Find $\nu_{max} = 7 \times 10^{12}$ Hz, i.e., $\lambda \sim 40$ μm
Best wavelengths to look for planets in direct emission are in the mid-IR, as the star's own spectrum drops

Another curiosity: dilluted starlight has an energy density much lower than that corresponding to its temperature - i.e., has a lower entropy. Important for the photo-bio-chemistry?

Free-free radiation: Bremsstrahlung

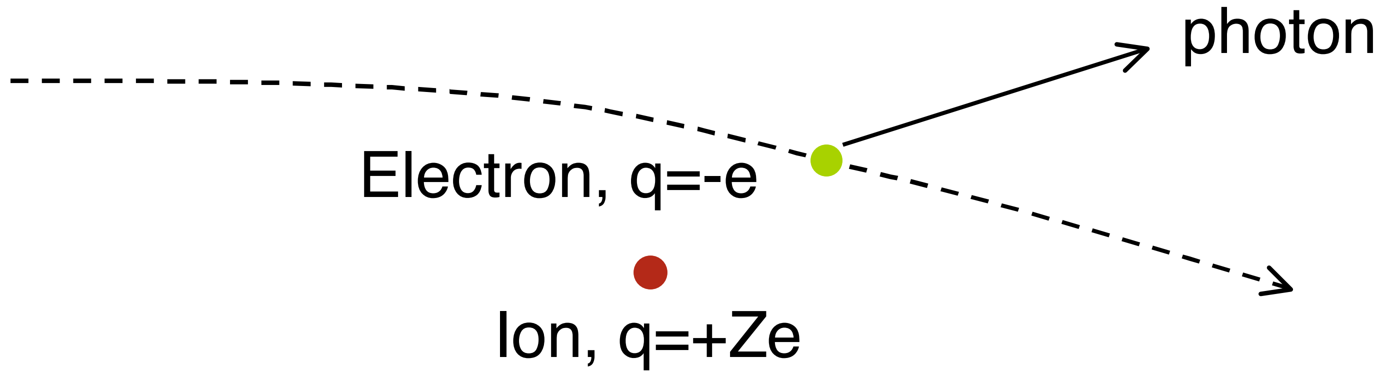
Hydrogen is ionized at T ~ 10^4 K at low density.

For the same mixture of chemical elements as the Sun, maximum radiation due to spectral lines occurs at T ~ 10^5 K.



At higher T, radiation due to acceleration of unbound electrons becomes most important.

Free-free radiation or **bremsstrahlung**.



`Collisions' between electrons and ions accelerate the electrons. Power radiated by a single electron is given by **Larmor's formula:**

$$P = \frac{2q^2}{3c^3}|\mathbf{a}|^2$$

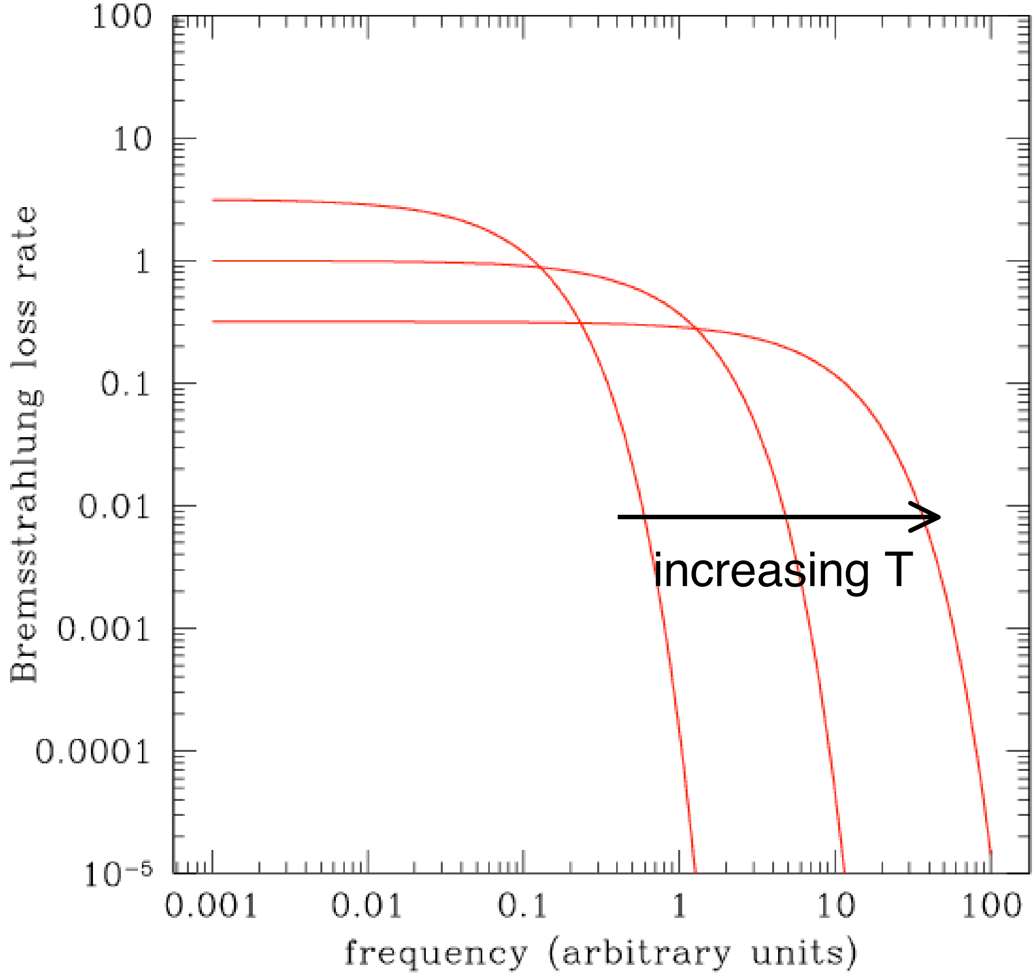
c.g.s. units: q is the charge, where electron charge = 4.80 x 10^{-10} esu. **a** is the acceleration, c is speed of light.

Prefer to work in SI? Larmor's formula:
…with q in Coulombs, ϵ_0 is the permittivity of the vacuum [10^7 / ($4\pi c^2$) C^2 N^{-1} m^{-2}]

$$P = \frac{q^2}{6\pi\epsilon_0 c^3}|\mathbf{a}|^2$$

Spectrum of bremsstrahlung

$$\epsilon_{\nu}^{ff} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \ \text{erg s}^{-1}\ \text{cm}^{-3}\ \text{Hz}^{-1}$$



Shape of bremsstrahlung spectrum

Flat spectrum up to an exponential cut off, at $h\nu = kT$.

Energy loss rate (overall and per Hz) depends on the **square** of the density.

Continuous spectrum.

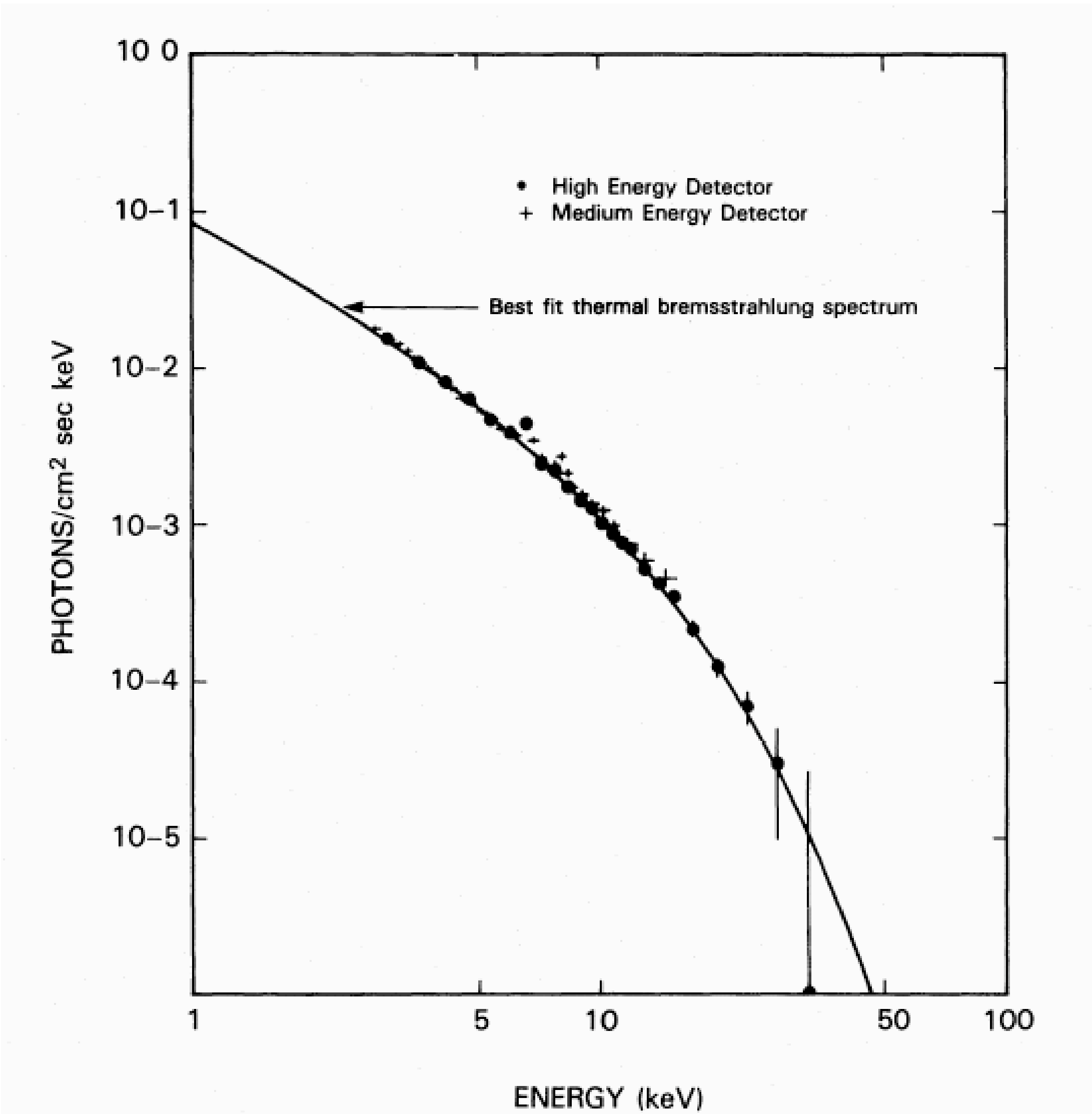
When is bremsstrahlung important?

Bremsstrahlung loss rate increases with temperature
Atomic processes become less important as the gas becomes fully ionized

} high T

Example: gas in the Coma cluster of galaxies

X-ray spectrum of Coma

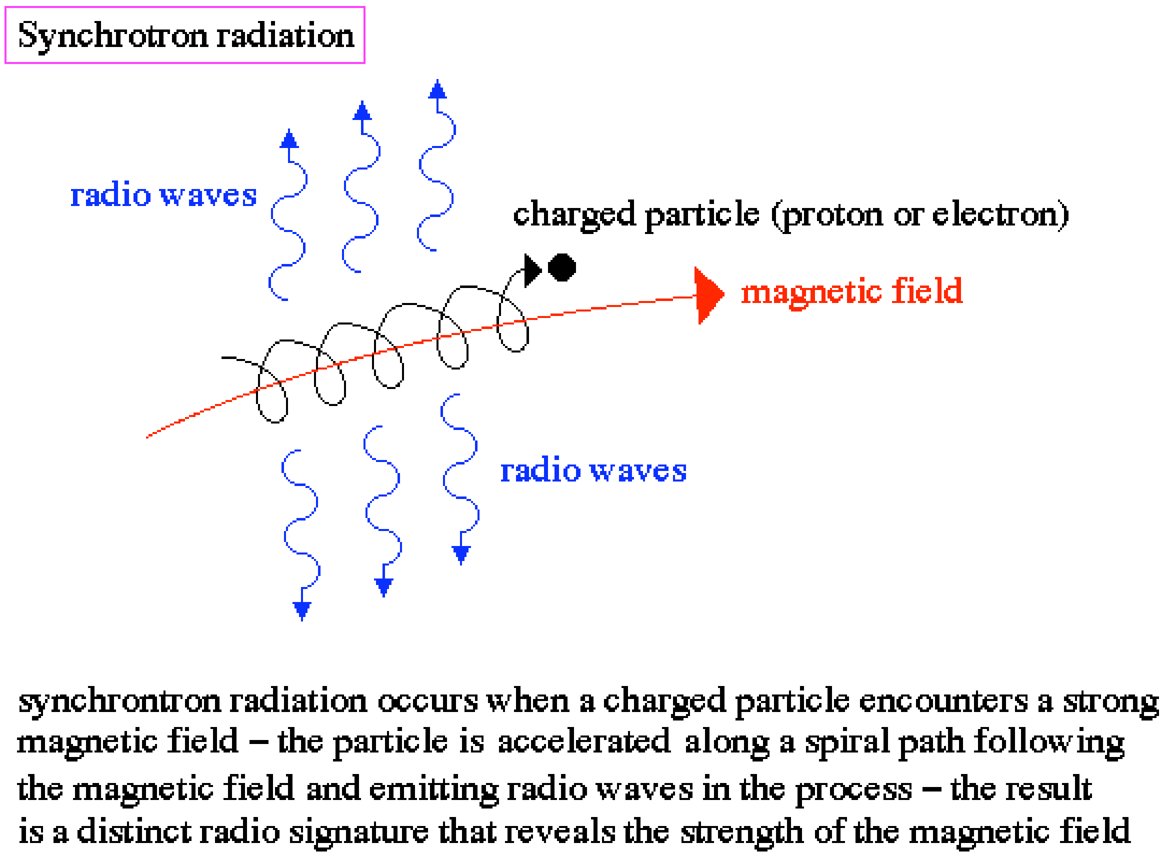


Shape of spectrum gives the temperature.

Intensity (for a known distance) gives the density of the gas.

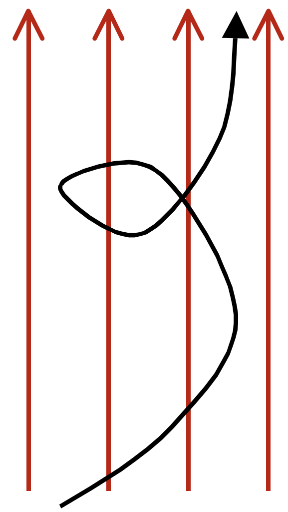
Galaxy cluster: find T = 10 - 100 million K.

Synchrotron Radiation



- Polarization properties of light provides information on magnetic field geometry

Cyclotron and synchrotron radiation



Electron moving perpendicular to a magnetic field feels a Lorentz force.

→ Acceleration of the electron.

→ Radiation (Larmor's formula).

Define the Lorentz factor: $\gamma \equiv \dfrac{1}{\sqrt{1 - v^2/c^2}}$

Non-relativistic electrons: ($\gamma \sim 1$) - **cyclotron radiation**

Relativistic electrons: ($\gamma >> 1$) - **synchrotron radiation**

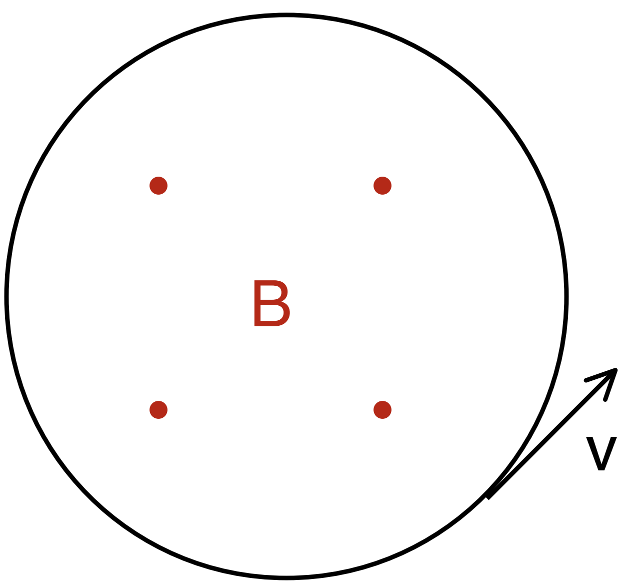
Same physical origin but very different spectra - makes sense to consider separate phenomena.

Start with the non-relativistic case:

Particle of charge q moving at velocity **v** in a magnetic field **B** feels a force:

$$\mathbf{F} = \frac{q}{c}\mathbf{v} \times \mathbf{B}$$

Let v be the component of velocity perpendicular to the field lines (component *parallel* to the field remains constant). Force is constant and normal to direction of motion.

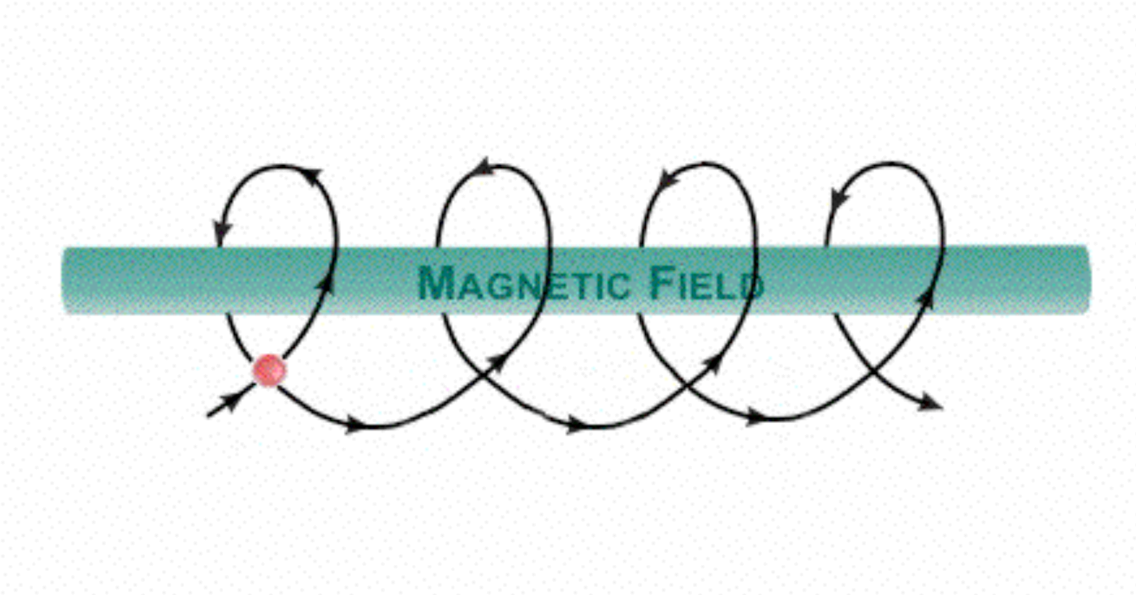


Circular motion: acceleration -

$$a = \frac{qvB}{mc}$$

…for particle mass m.

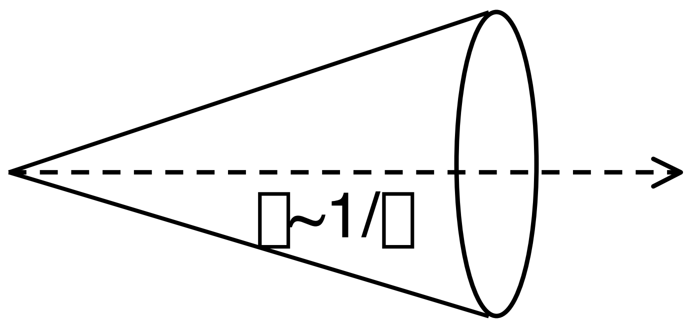
Syncrotron Emission



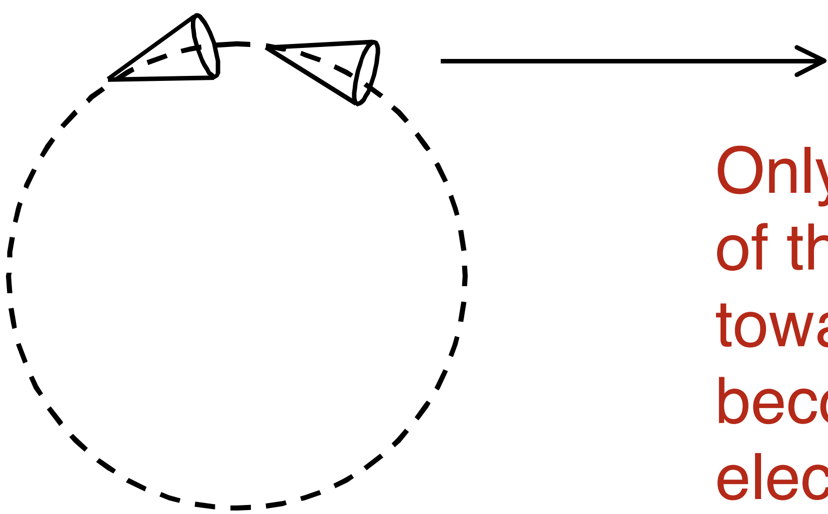
Synchrotron radiation

If the electrons are moving at close to the speed of light, two effects alter the nature of the radiation.

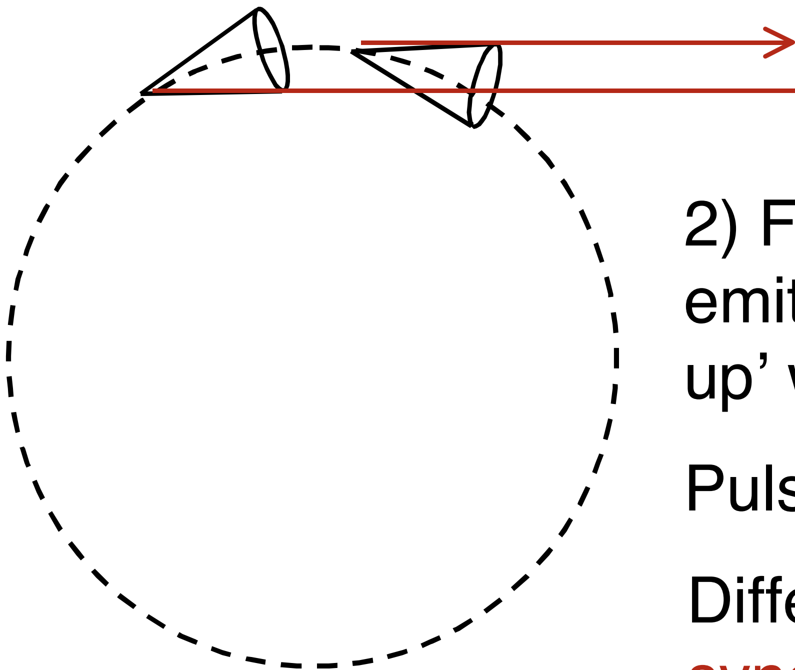
1) Radiation is **beamed**:



Particle moving with Lorentz factor □toward observer emits radiation into cone of opening angle: □□□[□1]



Only see radiation from a small portion of the orbit when the cone is pointed toward us - pulse of radiation which becomes shorter for more energetic electrons.



2) For source moving at v ~ c, photon emitted at end of pulse almost `catches up' with photon from start of pulse.

Pulse is further shortened.

Difference between **cyclotron** and synchrotron radiation.