OVERVIEW.

Coverage

Atoms + ions + molecules + radiation

non-relativistic

Aim:

Understand spectra of astronomical objects

Radiation

carries ~ all info learned by astronomers,

other sources? • neutrinos • grav waves
• cosmic rays • meteorites
• what spacecraft can gather in sol sys
• dark matter ??

Properties of radiation?:

- frequency ν
- direction
- flux $\frac{\text{photons}}{\text{area} \cdot \text{time}}$
- 2 polarizations (= spins)
- time dependence

$\Rightarrow$ information about emitting / absorbing source?

- density
- temperature
- composition spectral lines of different species
- velocity affects freq Doppler shift (= redshift)
- magnetic field affects: • freq Zeeman splitting
  • pol Faraday rotation

Atomic units

What spectral lines are most important in astronomy?
Determined by basic properties of atoms.

Structure of H-like ions
nucleus charge Ze
+ 1 electron

H-like He

is determined by 3 constants

e or more generally Ze^2 (why?)

m_e or more correctly reduced mass $\frac{m_e m_Z}{m_e + m_Z}$

$\hbar$ why need QM to understand atoms.

$\boxed{e = m_e = \hbar = 1}$ defines atomic units (a.u.)

$\alpha \equiv \frac{e^2}{\hbar c}$, $\approx \frac{1}{137}$ = fine structure constant

gaussian units commonly used by astron

dimensionles measure of strength of e.m. force

In SI units $\alpha = \frac{e^2}{4\pi \hbar c}$

Typical velocity of atomic electron

$v_{atom} \sim \frac{Ze^2}{\hbar} = Z\alpha c = \frac{Zc}{137} \ll c$ if $Z \ll 137$

what is non-rel?

$\Rightarrow$ non-relativistic, if Z is small.

But relativistic "fine-structure" effects get more important in heavier atoms like

Fe $Z = 26$. (why did I choose Fe?)

r_{atom} typical orbital radius of atomic electron

$\hbar \sim m_e v r$

$$\Rightarrow r \sim \frac{\hbar}{m_e v} \sim \frac{\hbar}{m_e Z \alpha c} \sim \frac{\hbar^2}{Z e^2 m_e}$$

$$a_0 \equiv \frac{\hbar^2}{e^2 m_e} = .529 \times 10^{-8}\ \text{cm} \approx 1\ \text{Å}$$

Bohr radius

$1\ \text{Å} \equiv 10^{-8}\ \text{cm} = 10^{-10}\ \text{m} = 0.1\ \text{nm}$

All these units commonly used by astronomers.

Typical collision cross-section

$$\sim \pi a_0^2 \sim 1\ \text{Å}^2 = 10^{-16}\ \text{cm}^2$$

t_{atom} typical orbital time of atomic electron

$$t \sim \frac{r}{v} \sim \frac{\hbar}{m_e v^2} \sim \frac{\hbar}{m_e Z^2 \alpha^2 c^2} \sim \frac{\hbar^3}{Z^2 m_e e^4}$$

$$\sim \frac{a_0}{\alpha c} = 2.42 \times 10^{-17}\ \text{s}$$

By comparison a typical radiative transition probability for "allowed" transition is $(10^{-8}\ \text{s})^{-1}$

$\Rightarrow$ excited atom does $\sim 10^9$ orbits before decaying

$\Rightarrow$ (a) radiation is very small perturbation to atom (down by factors of $Z^4 \alpha^3$)

(b) $\frac{\Delta E}{E} \sim \frac{\hbar / \Delta t}{\hbar / t} \sim 10^{-9}$

decay time

t_{atom}

E_{atom} typical orbital KE of atomic electron

$$\sim \frac{1}{2} m_e v^2 \sim \frac{1}{2} m_e Z^2 \alpha^2 c^2 \sim Z^2 \frac{m_e^2 e^4}{2\hbar^2} = Z^2 \text{ Ryd}$$

$$1 \text{ Rydberg} \equiv \frac{m_e^2 e^4}{2\hbar^2} = 13.6 \text{ eV} \approx \text{ionization potential of H.}$$

Two regimes for level populations of atoms & ions

why do these dominate? why?

(a) High density eg stellar atmosphere

Collision frequency $\gtrsim$ radiative rate

$$n\,\sigma\,v \gtrsim A$$

what here?

$$n \times 10^{-16}\,\text{cm}^2 \times 10^8\,\text{cm/s} \gtrsim 10^8\,\text{s}^{-1}$$

$$\Rightarrow \quad n \gtrsim 10^{16}\,\text{cm}^{-3}$$

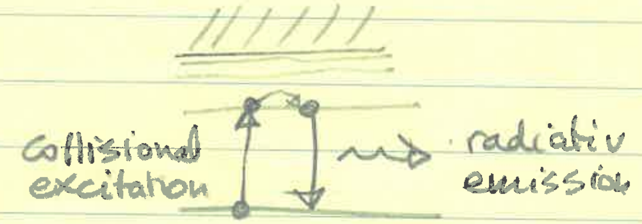
How big is this?

$\Rightarrow$ $\boxed{\text{T.E.}}$ is 1st approx for level populations.

why?

(b) Low density eg. interstellar space
uiter planetary

$n \lesssim 10^{16}\ cm^{-3}$



radiative rate
$>$ collision frequency

$\Rightarrow$ $\boxed{\text{nebular approximation}}$ = everything in ground state
is 1st approx for level populations.

Velocity distribution
of non-relativistic electrons = TE
atoms
ions
molecules

almost always.
Why?
Photons have lots of energy (so can excite atoms)
but little momentum (so don't change velocities).
Elastic collisions dominate energy exchange
means? $e + X \leftrightarrow e + X$
$\Rightarrow$ TE.