THE INTERSTELLAR MEDIUM (ISM) Oct-22-20

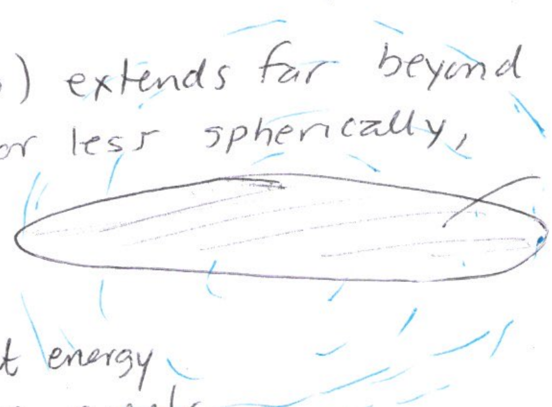
• The space between stars is filled with matter. The density is much lower than the best vacuum achievable on earth, but the distances between stars is huge, so there is a lot of mass. <u>This mass is critical for the structure, dynamics, and evolution of galaxies.</u>

• Most of the mass is in the form of hydrogen and helium:

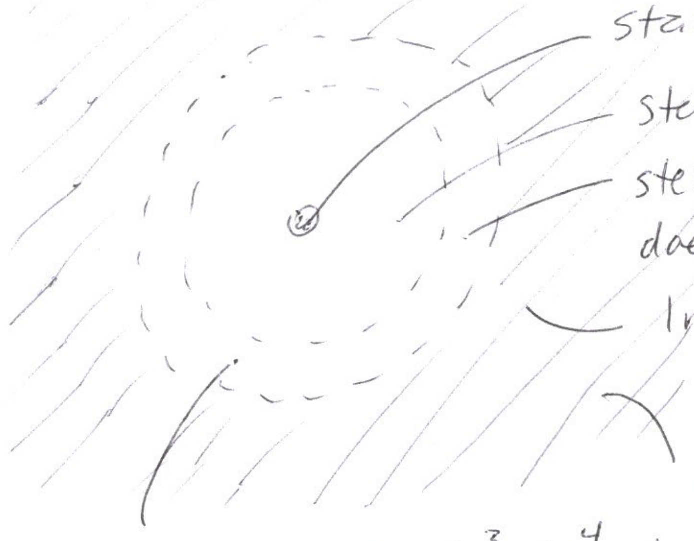
neutral hydrogen	(H I)	one proton and one electron
ionized hydrogen	(H II)	essentially just p^+ a proton
molecular hydrogen	(H_2)	two protons, two electrons, two nuclei
neutral helium	^3He, ^4He	two protons in single nucleus, two e^-
ionized helium		no e^-

By mass, about 70% hydrogen, about 30% helium
About 2-3% everything else, enriched by the "cyclical" process of star formation (birth and death).

Ionized corona (or halo) extends far beyond galactic plane, more or less spherically, with temperatures 10^6 K
$10^{-2} - 10^{-4}$ atoms per cm^3,
gravitationally bound, but energy comes from supernova, etc. events



Cold molecular clouds in the galactic plane, 50K - 150K, star formation
~10 atoms/cm^3



star

stellar wind displaces ISM material

stellar wind ionizes ISM material but does not displace it, creating HII regions

Interstellar medium, mostly unionized hydrogen HI regions

Density of about 10^1 atoms/cm^3

Density of about $10^3 - 10^4$ atoms/cm^3

Other ingredients of ISM

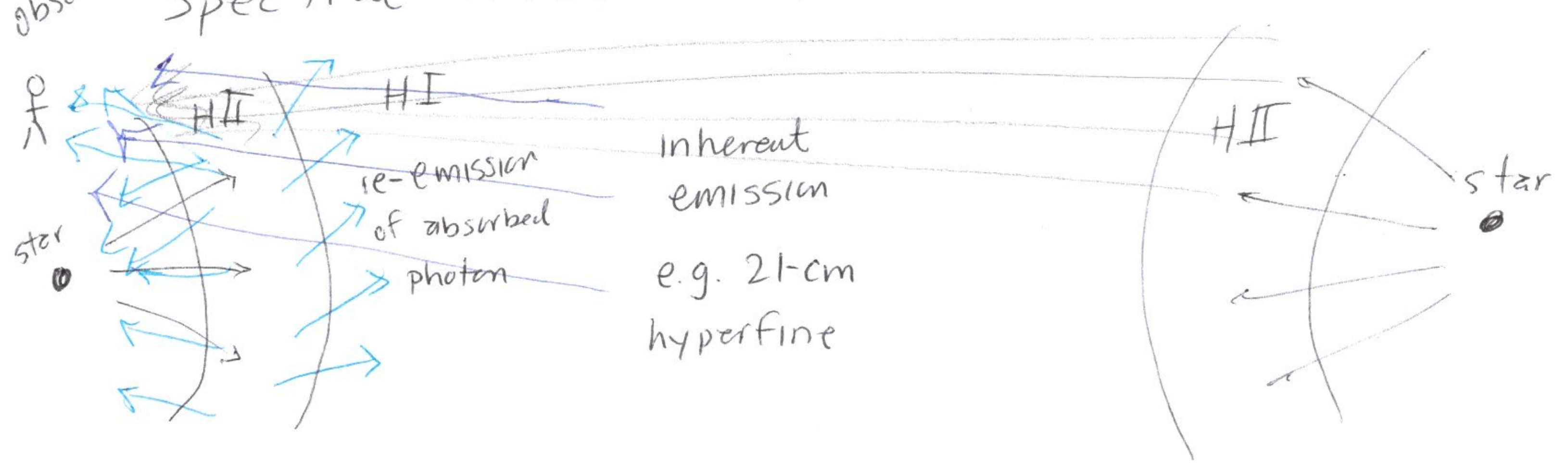
- "Metals" Carbon, nitrogen, oxygen } most abundant

  other atoms lithium, sodium, magnesium, aluminum, silicon, phospharus, sulfur, calcium, iron } measurable

- Dust Grains of solid matter, ~~mostly~~ made out of metals, 10^{-4} cm^3 in size, or less

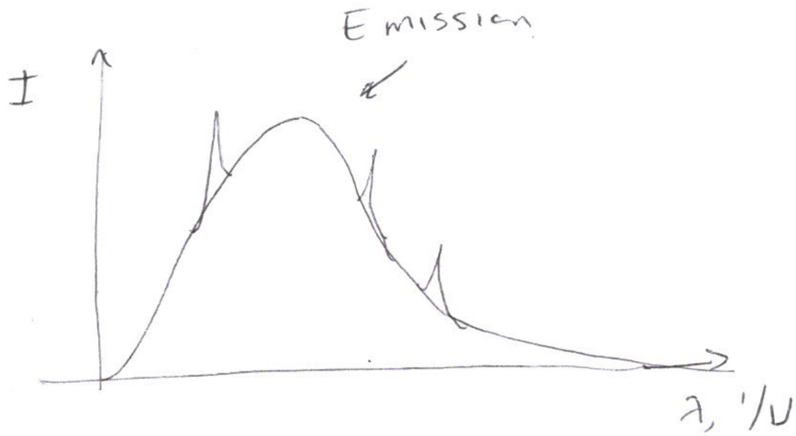
---

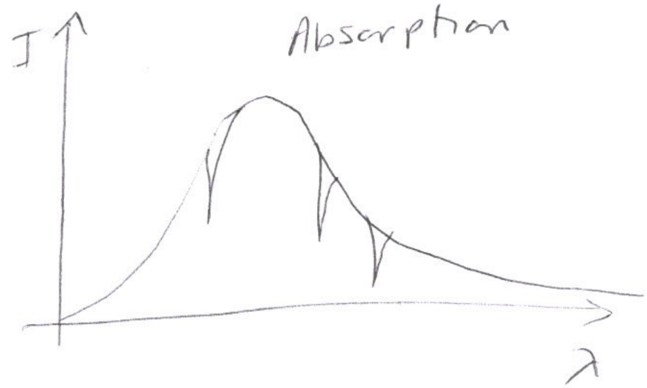
Spectral lines (emission and absorption)



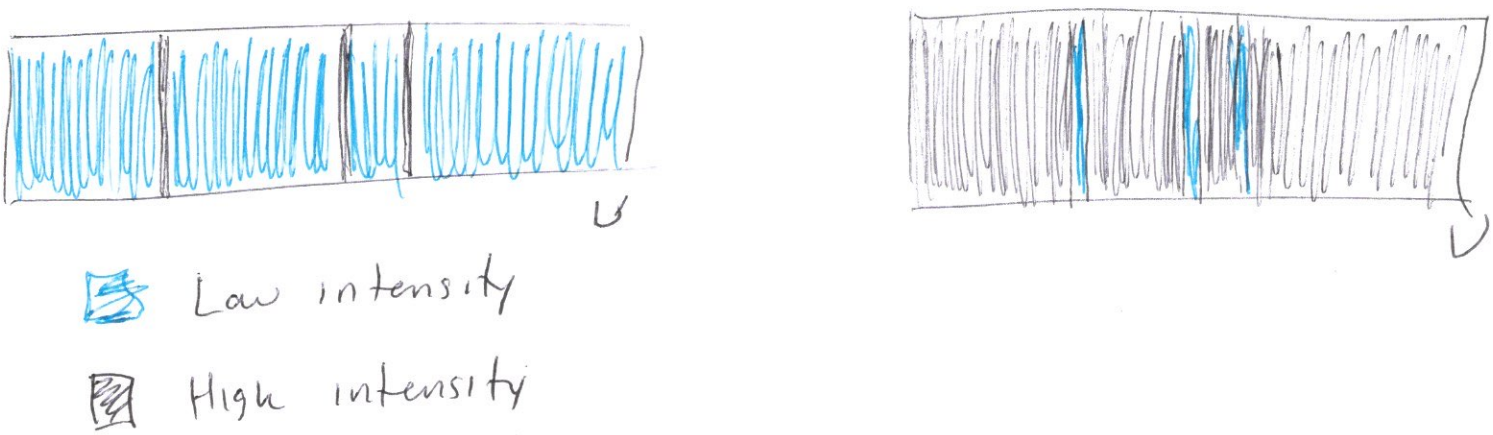
"reflection" "inherent" "absorption"

The emission/absorption is on top of the black body radiation spectrum, although these clouds are sparce and tend to be cold, so the intensity of black-body radiation can be low.





Correcting for the background, spectroscopy usually looks



★ WHAT PRODUCES THESE SEEMINGLY DISCRETE EMISSION/ABSORPTION LINES?

The Romans knew that a prism can separate white light into a rainbow, Newton was the first to develop a theory of optics, In 1802, William Hyde Wollaston combined a lens with a prism, focused the light from

Opticks published in 1704

the sun and discovered absorption lines. He thought that they were boundaries between colors.

Joseph von Fraunhofer replaced the prism with a diffraction grating, eventually with thousands of slits. This allowed experiments and measurements to be quantitatively reproducible. He independently re-discovered the absorption lines in the sun's spectra and they are now known as Fraunhofer lines.

In 1756 Thomas Melvill discovered emission lines when adding salts to alcohol flames. In 1835 Charles Wheatstone discovered that elements could be identified by their emission lines and Foucault demonstrated experimentally that emission and absorption lines for a given material are the same, depending on the temperature which one you get (1849). Independently, Ångström theorized the same thing in 1853.

In the 1860's Bunsen and Kirchhoff established spectrochemical analysis and discovered the elements Caesium and Rubidium. Also in this decade husband and wife William and Margaret Huggins showed that stars are composed of the same elements found on earth and used Doppler shift in 1868 to measure the axial speed of Sirius.

Also in 1868, Jules Janssen discovered helium in the spectrum of the chromosphere of the sun during a solar eclipse.

The Balmer lines are emission lines in hydrogen known since the 1860s, but it was Johan Balmer who in 1885 came up with the following empirical equation to predict them.

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \qquad n = 3, 4, 5, \ldots$$

R is the Rydberg constant $1.097 \times 10^7 \ m^{-1}$

$0.01097 \ /nm$

H_α is for $n=3$

$$\frac{1}{\lambda} = \frac{0.01097}{1nm}\left(\frac{1}{4} - \frac{1}{9}\right) = \frac{0.01097}{1nm}\left(\frac{5}{36}\right)$$

$$\frac{1}{\lambda} = \frac{0.001524}{1nm} \Rightarrow \lambda = \frac{1nm}{0.001524} = 656.3nm$$

H_β is for $n=4$

$$\frac{1}{\lambda} = \frac{0.01097}{1nm}\left(\frac{12}{64}\right) = \frac{0.002057}{1nm}$$

$$\Rightarrow \lambda = \frac{1nm}{0.002057} = 486.2 \ nm$$

H_γ, $n=5$

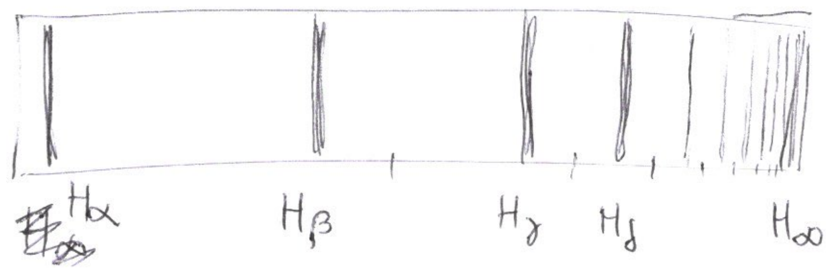
$$\frac{1}{\lambda} = \frac{0.01097}{1nm}\left(\frac{21}{100}\right) = \frac{0.002304}{1nm} \Rightarrow \lambda = 434.0 \ nm$$

H_δ, $n=6$

$$\frac{1}{\lambda} = \frac{0.01097}{1nm}\left(\frac{32}{144}\right) = \frac{0.002438}{1nm} \Rightarrow \lambda = 410.2 \ nm$$

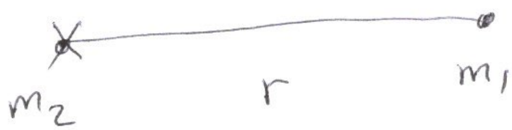
H_∞, $n = \infty$, $\dfrac{1}{\lambda} = \dfrac{0.01097}{1\,nm}\left(\dfrac{1}{4}\right) = \dfrac{0.002743}{1\,nm}$

$\Rightarrow \lambda = 364.6\ nm$



*WHAT IS THE ORIGIN OF THIS RELATIONSHIP?

Consider the model for binary compact objects, but with $m_2 >> m_1$ and $R_1 << r$. Also, origin of force is Coulomb interaction



$$F_{cent} = \frac{m_1 v^2}{r}$$

$$F_{elec} = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}$$

If the orbit is stable, then $F_{cent} = F_{elec}$, let's call m_1 and m_2 what they are, m_e & m_p.

$$\frac{m_e v^2}{\cancel{r}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^{\cancel{2}}} \Rightarrow v = \left(\frac{e^2}{4\pi\varepsilon_0 m_e r}\right)^{1/2} = \frac{e}{\sqrt{4\pi\varepsilon_0 m_e r}}$$

$$KE = \frac{1}{2}m_e v^2 = \frac{1}{2}\cancel{m_e}\frac{e^2}{4\pi\varepsilon_0 \cancel{m_e} r} = \frac{e^2}{8\pi\varepsilon_0 r}$$

$$\text{Total} = \frac{e^2}{8\pi\varepsilon_0 r} - \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}$$

$$E = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}\left(\frac{1}{2} - 1\right) = -\frac{e^2}{8\pi\varepsilon_0 r}$$

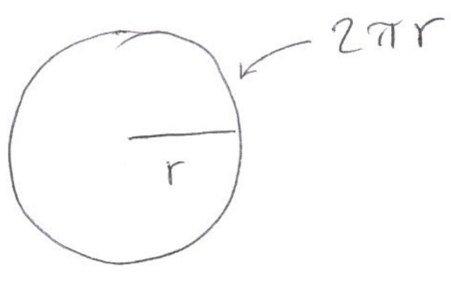
Expected?

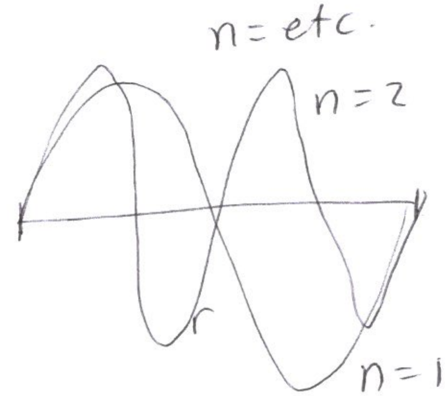
The ~~de~~ de Braglie wavelenght of such electron is

$$\lambda = \frac{h}{p} = \frac{h}{m_e v} = \frac{\frac{h}{1}}{\frac{m_e \quad e}{\sqrt{4\pi\varepsilon_0 m_e r}}} = \frac{h\sqrt{4\pi\varepsilon_0 m_e r}}{e \quad m_e}$$

$$\lambda = \frac{h}{e}\sqrt{\frac{4\pi\varepsilon_0 \cancel{m_e} r}{m_e^{\cancel{2}}}} = \frac{h}{e}\sqrt{\frac{4\pi\varepsilon_0 r}{m_e}}$$

This wavelenght has to wrap around in a loop, otherwise it interfeers with itself.





For $n = 1$

$$2\pi r = \frac{h}{e}\sqrt{\frac{4\pi\varepsilon_0 r}{m_e}} \Rightarrow \cancel{4}\pi \cancel{^2} r^{\cancel{2}} = \frac{h^2}{e^2}\frac{\cancel{4\pi}\varepsilon_0 \cancel{r}}{m_e}$$

permitivity of free space

$$\Rightarrow \frac{h^2\varepsilon_0}{\pi e^2 m_e} = r = \frac{(6.626\times10^{-34}\,J\cdot s)^2(8.85\times10^{-12}\,C^2/N\cdot m^2)}{\pi(1.602\times10^{-19}\,C)^2(9.11\times10^{-31}\,kg)}$$

$$r = \frac{\left(4.39\times10^{-67}\ N^{\cancel{2}}\,\cancel{m^2}\,s^2\right)\left(8.85\times10^{-12}\ \frac{\cancel{C^2}}{\cancel{N}\,\cancel{m^2}}\right)}{\left(8.06\times10^{-38}\ \cancel{C^2}\right)\left(9.11\times10^{-31}\ kg\right)}$$

$$r = \frac{\left(3.88\times10^{-78}\ \frac{\cancel{kg}\,m}{\cancel{s^2}}\ \cancel{s^2}\right)}{7.34\times10^{-68}\ \cancel{kg}} = 5.3\times10^{-11}\ m$$

This is known as the Bohr radius, usually a_0

remember that the fine structure constant is $\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$,

so $\varepsilon_0 = \frac{1}{4\pi\alpha}\frac{e^2}{\hbar c}$

$$a_0 = \frac{(2\pi\hbar)^2}{\pi \cancel{e^2} m_e}\,\frac{1}{4\pi\alpha}\,\frac{\cancel{e^2}}{\hbar c} = \frac{\cancel{4\pi^2}\,\hbar^{\cancel{2}}}{\cancel{4\pi^2}\,\cancel{\hbar}\,m_e c\alpha} = \frac{\hbar}{m_e c\alpha}$$

The Bohr radius is the most probable distance between the electron and proton in a hydrogen atom in its ground state. It was derived by Niels Bohr in 1913 using quantization of the angular momentum (de Broglie had not yet discovered the de Broglie wavelenght). It made every body uncomfortable, but it works.

More generally, $n\lambda = 2\pi r_n$, where n is called the quantum number of the orbit.

$$2\pi r_n = n\frac{h}{e}\sqrt{\frac{4\pi\,\varepsilon_0 r}{m_e}} \Rightarrow \cancel{4}\pi^{\cancel{2}} r_n^{\cancel{2}} = \frac{n^2h^2}{e^2}\,\frac{\cancel{4\pi}\,\varepsilon_0 \cancel{r_n}}{m_e}$$

$$\Rightarrow r_n = \frac{n^2h^2\varepsilon_0}{\pi m_e e^2}$$

Since $a_0 = \dfrac{h^2\varepsilon_0}{\pi m_e e^2}$, $r_n = n^2 a_0$

Before we had derived $E = -\dfrac{e^2}{8\pi\varepsilon_0 r}$, so

$$E_n = -\frac{e^2}{8\pi\,\varepsilon_0 r_n} = -\frac{e^2/1}{8\cancel{\pi}\,\varepsilon_0\,\dfrac{n^2h^2\varepsilon_0}{\cancel{\pi} m_e e^2}}$$

$$E_n = -\frac{m_e e^4}{8\varepsilon_0^2 h^2}\left(\frac{1}{n^2}\right)$$

Since $E_1 = -\dfrac{m_e e^4}{8\varepsilon_0^2 h^2}$, $E_n = \dfrac{E_1}{n^2}$

$$E_1 = -\frac{(9.11\times10^{-31}\,\mathrm{kg})(1.602\times10^{-19}\,\mathrm{C})^4}{8\left(8.85\times10^{-12}\,\dfrac{\mathrm{C}^2}{\mathrm{N\cdot m^2}}\right)^2\left(6.626\times10^{-34}\,\mathrm{J\cdot s}\right)^2}$$

$$E_1 = -\frac{6.0\times10^{-106}\ \mathrm{Kg}\ \cancel{C^4}}{\left(6.26\times10^{-22}\ \frac{\cancel{C^4}}{\cancel{N^2}\ m^{\cancel{4}2}}\right)\left(4.39\times10^{-67}\ \cancel{N^2}\ \cancel{m^2}\ s^2\right)}$$

$$E_1 = -\frac{6.0\times10^{-106}\ \mathrm{Kg}}{2.75\times10^{-88}\ \frac{s^2}{m^2}} = -2.18\times10^{-18}\ \frac{\mathrm{Kg}\,m^2}{s^2}$$

$$E_1 = -2.18\times10^{-18}\ J = -13.6\ eV$$

Let $\Delta E = h\,\Delta\nu = E_i - E_f$

E_i is the initial (higher energy) state and

E_f is the final (lower energy) state.

$$E_i - E_f = \frac{E_1}{n_i^2} - \frac{E_1}{n_f^2} = E_1\left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right) = -E_1\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

$$\nu = \frac{E_i - E_f}{h} = -\frac{E_1}{h}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

with $\lambda = \frac{c}{\nu}$, $\frac{1}{\lambda} = \frac{\nu}{c}$

This was $\frac{1}{2^2}$ for the Baldmer series. What does it mean?

$$\frac{1}{\lambda} = -\frac{E_1}{hc}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = -\frac{\left(-2.18\times10^{-18}\ \cancel{J}\right)}{\left(6.626\times10^{-34}\ \cancel{J}\cdot\cancel{s}\right)\left(3\times10^{8}\ \frac{m}{\cancel{s}}\right)}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

$$\frac{1}{\lambda} = \frac{2.18\times10^{-18}}{1.99\times10^{-25}\ m}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = 1.097\times10^{7}\ m^{-1}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$