Pynbody

12/03/19

→ To login : Open a new terminal & type :

~~ssh~~ ssh -X amasin@cluster.s3it.uzh.ch

& then enter pswd.

→ ls to see ~~jobs~~ job.sbatch file in the directory

→ type: less job.sbatch (to see the last session by opening the file ('Q' to exit later)

→ To renew a request after 24 hrs :

sbatch job.sbatch

→ To see your name in the queue of tasks :

squeue → to look at all requests by everyone

squeue ~~xxxx~~ -u amasin → for my requests only (select the latest one)

→ To see the current request by opening the new request file :

less log_*****.txt → the alphanumeric name of the most recent request. (A)

→ To get into bulk :

~~xxxx~~ cd /bulk1/teyssier/mkrets → Michael's directory

to make a "soft"-link of the above path so that you don't have to type the address everytime :

~~xx~~ ln -s /bulk1/teyssier/mkrets bulk1

→ Assigning this path to this keyword.

3/19

→ Now instead of typing: cd /bulk1/teyssier/mkrets/ , type : cd bulk1

→ To copy a file from Michael's directory to my home directory :

$$\underbrace{\text{cp}}_{\text{for copy}} \quad \underbrace{\text{filename.py}}_{\text{the file to be copied}} \quad \underbrace{\sim/.}_{\text{signifies my home directory}}$$

To start Jupyter notebooks :

(From the blue part) A

① After opening the file log-.... txt, there will be a command written on top :

ssh -N -L 4169 : $\underbrace{\text{. . . .}}_{\text{IP (secure)}}$: 4169 amasin@-.-.-.ch

② Copy this into a completely new Terminal, & paste+enter.

③ Enter pswd.

① Now open a web-browser :

② Copy the link at the bottom of this file.

③ Paste it in the browser

④ Jupyter N.b.

→ Now instead of typing: cd /bulk1/teyssier/mkrets/ ,
type : cd bulk1

→ To copy a file from Michael's directory to my home directory :

$$\underbrace{\text{cp}}_{\text{for copy}} \quad \underbrace{\text{filename.py}}_{\text{the file to be copied}} \quad \underbrace{\sim/.}_{\text{signifies my home directory}}$$

To start Jupyter notebooks :

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④ Jupyter N.b.

$m_p = [g]$

$\rho = [g/cm^3]$

$n_H = \rho / m_p = [\#/[cm^3]]$

$\overline{n}_H = 100$

$\Rightarrow \overline{\rho}_H = n_H * m_p$

$= 100\, m_p$

From sim. :

ρ, M, cs, Z

$n_{H,mean} = 100$

$\rho_{mean} = n_{H,mean} * m_p$ (A)

$s =$ np.log (ρ / ρ_{mean})

pdf = ___

λ_J = ___

n_{LW} = ___

X_{H2} = ___

Either define

$m_p = 1.67 \times 10^{-27}$ kg

so that

$\rho / \rho_{mean} =$ dimless

OR

Define

$\rho_{mean} = n_{H,mean} \times 1.67 \times 10^{-27}$ kg

where $n_{H,mean}$ = vary

so that

ρ / ρ_{mean} = dimless

---

(1) X_{H2} → self shielding

(2) $\overline{X}_{H2}$ vs $\overline{n}_H$ → by varying M, Z

size(M)

size(Z)

13/03/2019

X_H2.py

① Importing

```
import numpy as np ; import matplotlib.pyplot as plt ;
import pynbody ; from michaels_functions import center_and_r_vir, remove_bulk_velocity
```

```
② path = "bulk1/data_2/hydro_59/output/"
data = pynbody.load(path + "output_00050")
aexp = data.properties['a']
data.physical_units()
print path
print "a =", aexp
print "z =", 1./aexp - 1

③ r_vir = center_and_r_vir(data, aexp, path)

④ r_e = 0.1 * r_vir
print r_e

⑤ sph_5 = pynbody.filt.Sphere(radius = '%f kpc' %(r_e*1.0))
region = data[sph_5]

⑥ rho = region.gas["rho"].in_units("m_p cm^-3")
Z = region.gas["metal"]

⑦ f = open(data.filename + "/info_" + data.filename[-5:]+".txt", "r")
lines = f.readlines()
f.close
for line in lines:
    if line[0:13] == "unit_l =":
        print line[:-1]
        unit_l = float(line[14:-1])

    if line[0:13] == "unit_d = ":
        print line[:-1]
        unit_d = float(line[14:-1])
```

```
if line[0:13] == "unit_t = ":
    print line[:-1]
    unit_t = float(line[14:-1])
if line[0:13] == "omega_b = ":
    print line[:-1]
    omega_b = float(line[14:-1])
```

(8)
```
turb = np.sqrt(region.g["turb"] * 2.0/3.0) *
                    unit_l /unit_t /1e5

turb = pynbody.array.SimArray(turb, units = "km s**-1")

cs = np.sqrt(region.gas["p"] / region.gas["rho"])
            cs = cs.in_units("m s**-1")

# for non-isothermal, γ ≠ 1 , γ = 4/3
# ∴ cs = np.sqrt( 4.0/3.0 * region.gas .... )

M = turb/cs
region.g["mach"] = M.in_units("1")
```

(9) turb
(10) c_s] → Just to check units
(11) M

(12)
```
m_p = pynbody.array.SimArray(1.0, pynbody.units.m_p)
   n_H = rho/m_p
```

(13) n_H] → Units check

(14) K_b =

→ To see

→ To sea

→ Direct

cd bulk

This
has
of m
some
ellipt
are
They

→ In

Eg

14/03/2019

→ To see only one type of files :

ls log_1* → to show all the log files

ls *.txt → to show all the txt files

→ To remove all the log files :

rm log_1*

$\underbrace{\text{rm}}$ → "remove"

→ Directory structure :

cd bulk1/data_2/hydro_59/output

data_2 → This folder has snapshots of many galaxies some spherical, some elliptical. Best galaxies are hydro_50's They have the best resolution.

hydro_59 → Galaxy no. 59 contains material that is not of any use to me

output → Folder contains output snapshots (numbered : output_00001 to _00148), .mp4 movies, txt files etc.

00001 → very high redshift, prolly $z \sim 100$

00148 → right now $z = 0$

→ In the output folder :

- Output_00001 to output_00148

↳ different folders for diff. redshifts.

Eg: take output_00020 & open it

cd output_00020

Now this folder has all the info in it. The info is stored in the info.txt file, so ~~opening~~ finding & open that :

ls *.txt

less info_00020.txt → this will have all info for $z, \Omega_b, \Omega_m, \Omega_k, \Omega_\Lambda(z)$ etc.

→ The snapshots don't have resolution that helps them zoom into ~~each cell~~ what's going on in each cell. So all the values stored in arrays are actually the mean values in each cell.

Eg: rho ← density array

↳ It has size 1,040,042

But all these values are $\bar{\rho}$ & not ρ

Because the simulation cannot see what's going on inside the cell, so it ~~assigns~~ just takes the mean value.

So for $n_{H,mean}$ → use $\cancel{\rho}$ array rho

① Load simulation to get : ρ, n_x, n_y, n_z, v_x, v_y, v_z, grad_v

② $T = 10$ K

$\mu = 2.37$

$$C_s = \sqrt{\frac{K_b T}{\mu \cdot m_H}}$$

③ Load the <u>LAMDA File</u> & calculate the C coeff. for each cell.

→ <u>Also</u> : freq, A, B, num_lvls, n_i, Z

④ If species == 'CO' :

UV_rad_field = n_{LW}

n_{H2} = calc_n_{H2}( )

n_{molec} = n_{co}

⑤ Set initial radiation field to the CMB (same for all cells)

↳ (this is in contradiction with how n_{co} is calculated)

```
rad_field_CMB = np.zeros ((num_lvls, num_lvls))
T_bg = 2.73    # CMB temp. background

for i in range (num_lvls):
    for j in range (num_lvls):
        if freq.[i][j] != 0.0 :
            rad_field_CMB [i][j] = B_nu_ev (freq[i][j], T_bg)
                                          # eV/m2
```

⑥ num_iter = 10 → max. no. of iterations for solving lvl population

$E \to cm^{-1}$

$\frac{hc}{\lambda} \to cm^{-1}$

$$E = \frac{hc}{\lambda} = \frac{eV \cdot \cancel{s} \cdot \cancel{cm}}{\cancel{cm} \cdot \cancel{s}} = eV$$

$$\frac{h\_ev * c\_cgs}{\lambda} = E \to eV$$

Theory

$B \to J^{-1} m^3 s^{-2}$

$= \frac{m^3}{J s^2}$

$= \frac{m^3 \cancel{s^2}}{kg\, \cancel{m^2}\, \cancel{s^2}} = \frac{m}{kg}$

$= \frac{10^2\, cm}{10^3\, g} = 10^{-1}\, cm/g$

Calc in code

$B = \frac{A \cdot (c_{cgs})^2}{2\, h\_ev \cdot freq}$

$= \frac{s^{-1} \cdot (cm\, s^{-1})^2}{eV \cdot s \cdot (Hz^3 \to \frac{1}{s})^3}$

$= \frac{cm^2 \cdot \cancel{s^3}}{s \cdot eV \cdot \cancel{s} \cdot \cancel{s^2}} = \frac{cm^2}{eV \cdot s}$

$$B = \frac{A c^2}{2 h \nu^3} = \frac{s^{-1} (cm/s)^2}{g\, cm^2 s^{-2}\;\; s^{-3}}$$

$$= \frac{\cancel{cm^2}\, \cancel{s^2}\, s^3}{\cancel{s^2}\, g\, \cancel{cm^2}} = s^3/g$$

	File	Code	Tine
E	s^{-1}	eV	eV
freq	GHz	Hz	Hz
A	s^{-1}	s^{-1}	s^{-1}
B	–	$cm^2/eV \cdot s$	$cm^2/eV \cdot s$
C	cm^3/s	cm^3/s	m^3/s
C_s	–	cm/s	m/s

→ Packing

→ using Einstein's relation:
$B = [cm/g]$

$km = 10^3\, m$
$= 10^3 \times 10^2\, cm$
$= 10^5\, cm$

① Use full $\overline{n_H}$ & $\mathcal{M}$ in ($\overline{X_{H2}}$ vs $\overline{n_H}$)

② Try to use $\overline{n_H}$, $\mathcal{M}$ & Z in ($\overline{X_{H2}}$ vs $\overline{n_H}$)

③ Correct X_{H2}.py code

④ Radiative transfer :

(i) Complete everything as Tine & see if it works

(ii) Listen to audio & make everything again.

12/04/2019

→ c_s → calc. using $\sqrt{P/\rho}$] — Check if similar answers

↳ also has the formula $\sqrt{\frac{k_B T}{m_p n_H}}$

↳ Mach no. $\mathcal{M} = \frac{turb}{c_s}$ → from sim; c_s → from above prolly using temp.

Right now I am taking $\mathcal{M}$ as an array, so – no need for all this, just need T=10K for λ_J

But when doing sim., use T = temperature from sim.

↳ also, use the same temp. for c_s.

→ Make the iterations for SS faster – once done & tested, upload as a python script for full simulation.

→ Make another version of this using the analytical approximation that Prof. Teyssier told today.

→ Copy everything from Tine's RT code & eliminate/modify one by one.

```
def _(x):
  for (i -> x)
    if (i < x):
      ≡
    else:
      ~~temp1~~ n_LW,ss = temp1
      ~~temp2~~ X_H2 = temp2
        n_H2 = n_LW,ss * X_H2

  return n_LW,ss , X_H2, n_H2
```

break] → valid in
continue] Python too

```
def self_shielding (n_H, G_0, λ_J , Z ) :
  ctr = 10
  ~~for ...~~
  n_LW = calc_n_LW (n_H, G_0, λ_J)
  X_H2,a = calc_X_H2 ( n_H, Z, n_LW)
  n_H2,a = n_H * X_H2,a
  n_H2 = n_H2,a
  i=0
  while (i < ctr ):
    n_LW,ss, S_H2, N_H2 = calc_n_LW,ss ( n_H, n_H2 , G_0, λ_J)
    X_H2 = calc_X_H2 (n_H, Z, n_LW,ss)
    n_H2 = n_H * X_H2

  return n_LW,ss , X_H2, n_H2 , S_H2 , N_H2
```

$$c_s = \sqrt{\frac{K_B T}{m_p}} = \sqrt{\frac{cm^2\, g\, \cancel{K}}{s^2\, \cancel{K}\, \cancel{g}}} = cm/s$$

$N_{H2} = n_{H2} \cdot$

$S_{H2} = \frac{0.965}{\left[1 + \left(\frac{N_{H2}}{5e14}\right.\right.}$

12/04/19

$\frac{1}{\exp\left[-\frac{(\bar{\delta} - \delta_{crit})}{\Delta s}\right]}$

$\bar{X}_{H2}$ vs $\bar{n}_H$

remains

Idea : fit
Fermi

$\frac{1}{\exp\left[-\frac{(\bar{\delta} -}{\Delta}\right.}$

This Script
the fractio
"temperat
$\Delta\delta(M)$

$N_{H2} = n_{H2} \cdot \lambda_J \rightarrow \frac{g}{cm^3} \, cm = g/cm^2$

$$S_{H2} = \frac{0.965}{\left[1 + \left(\frac{N_{H2}}{5e14}\right)\right]^2} + \frac{0.035}{\sqrt{1 + \frac{N_{H2}}{5e14}}} \cdot \exp\left[- \frac{\left(1 + \frac{N_{H2}}{5e14}\right)^{1/2}}{1180} \right]$$

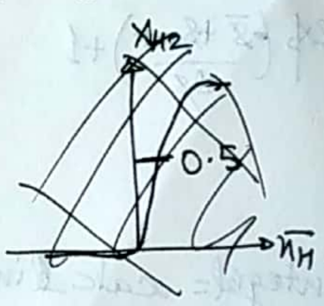
12/04/19

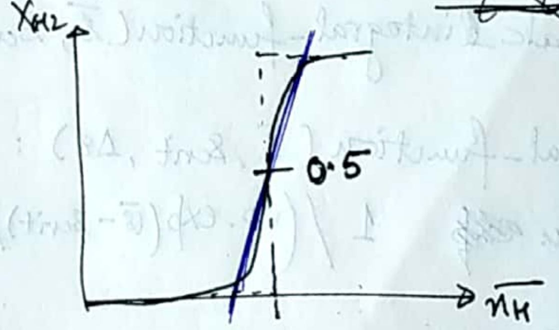
$s = \ln n_H$ $\quad \bar{s} = \ln \bar{n}_H$

$$\frac{1}{\exp\left[-\frac{(\bar{s} - s_{crit})}{\Delta s}\right] + 1}$$

$s_{crit}(M)$

$\Delta s(M)$





$\bar{X}_{H2}$ vs $\bar{n}_H$: for diff M, it shifts, but the shape remains the same.

Idea: fit this shape with a mathematical f^n that looks like a reversed Fermi-Dirac f^n (like a smoothed heaviside)

$$\frac{1}{\exp\left[-\left(\frac{\bar{s} - s_{crit}}{\Delta s}\right)\right] + 1} \rightarrow \text{functional form}$$

At very high densities $\rightarrow 1$
low $\rightarrow 0$

This s_{crit} controls the location of this thing, that's where the fraction is 0.5, & the Δs here would be the "temperature" for X_{H2}. Now, for each M, diff. $s_{crit}(M)$ & $\Delta s(M)$

δ_{crit} → a no. (not an array) at which $\bar{X}_{H2} = 0.5$

$\bar{\delta} = \ln \bar{n}_H$

Δs → either ds
or Temp T

$$\frac{1}{\exp\left(\frac{-\bar{\delta} + \delta_{crit}}{\Delta\delta}\right)+1} = \bar{X}_{H2}$$

integral= calc_integral_function($\bar{\delta}$, δ_{crit}, $\Delta\delta$)

```
def calc_integral_function(δ̄, δcrit, Δδ):
    X̄_H2 = 1 / (np.exp((δ̄ - δcrit)/Δδ) + 1)
    return X̄_H2
```

```
X̄_H2 = np.zeros(len(δ̄))
i=0
δcrit = 1.0
while(i<5):
    for j in range(0, len(δ̄)):
        X̄_H2[j] = (1 / np.exp((δ̄[j] - δcrit)/Δδ) + 1))**2
        if X̄_H2[j] = 0.48:
            δcrit = δ[j]
    i+=1
return X̄_H2, δcrit
```

$\bar{\delta} = \ln \bar{n}_H$

n_{co}

n_{co} =

Increase

Plot $\bar{X}_{co}$

→ integral

Metallici

now. – Ve

1.1 – I

1.2 – M

1.3 – $\bar{X}$

1.4 –

1.5 –

16/0

- $\bar{X}_{co}$ → form
- C_s → $\sqrt{}$
- Make M
- Look at

$$n_{CO} = n_{H_2O} \frac{Z}{0.02} \cdot X_{CO}\, 10^{-4}$$

n_H → metallicity in solar units

$$n_{CO} = n_{H_2O} X_{CO}$$

- Increase radius ⟹ increase time
- Plot $\bar{X}_{CO}$ vs $\bar{n}_H$
- → integral $\bar{X}_{H2}$ using analytical function.
- Metallicity + M + $\bar{n}_H$ & $\bar{X}_{H2}$
- ——— & $\bar{X}_{CO}$

now – Very First (5kpc – small)

1.1 — Initial – 5 kpc (small)

1.2 — Multiplied X_{H2} with 2 inside code – 5 kpc (small) Done (till 2am)

1.3 – $\bar{X}_{H2}$, $\bar{X}_{CO}$ – 15 kpc (full)

1.4 – $\bar{X}_{H2}$ & $\bar{X}_{CO}$ for $M, Z, \bar{n}_H$ – 5kpc (small)

1.5 – $\bar{X}_{H2}$ & $\bar{X}_{CO}$ for $M, Z, \bar{n}_H$ – 15kpc (full)

16/04/2019

- X_{CO} → formula correction → $K_{new} = K_{old} * \left(\frac{Z}{0.02}\right)$
- C_s → $\sqrt{\gamma P/\rho}$ or $\sqrt{\frac{K_B T}{m_p}}$ → see which one is better.
- Make M, Z, G_0 varying plots for $\bar{X}_{H2}$ & $\bar{X}_{CO}$ & keep them handy.
- Look at the paper from the Italian guys & look for : ① Defining G_0 values? ② How do they calc. C_s?

- ~~Make~~ M, Z, G_0 plots for old algorithm & keep them handy. → "reference" plots
- Make a pdf for all the plots till date – $\bar{X}_{H2}$ → viridis, $\bar{X}_{CO}$ → magma
- Read paper of Italian guys once again, & find:
  1. Defining G_0 values?
  2. How do they calc. c_s?
- Prepare for the meeting tomorrow!

---

① For old Algo reference plots:

5 kpc

$c_s = \sqrt{\frac{k_B T_{mean}}{m_p}}$ → λ_J only, not in M ⟷ (same)

$M = [\text{np.min}, \text{np.max}] - 5$ (0.032, 277.597) ⟷ $[\text{np.min}, \text{np.max}] - 5$ (0.032, 277.597)

$Z = [\text{——}] - 5$ (0.000425, 0.1139) ⟷ $[\text{——}] - 5$ (0.0003, 0.1139)

$G_0 = (0.1 - 100) - 5$ ⟷ $[0.1 - 100] - 5$

$\bar{n}_H = [\text{——}]\ 40$ (3e-5, 369.06)

15 kpc

$\bar{n}_H = [\text{—}]\ 40$ (2.41e-5, 369.06)

$\bar{X}_{H2}$ vs $\bar{n}_H$ & $\bar{X}_{CO}$ vs $\bar{n}_H$ – M, – Z, – G_0

$\bar{X}_{H2}$ vs $\bar{n}_H$ & $\bar{X}_{CO}$ vs $\bar{n}_H$ – M, – Z, – G_0

"Log scaling in scatter plots"

$M \to (-2, 3)$

$Z \to (-2, 3)$

$G_0 \to (-1, 3)$

$\bar{n}_H = (-5, 4, 40)$

sim: mean(M) = 3.77, mean(Z) = 0.007, mean(G_0) = —

H2 → viridis
CO → magma

17/04/2019 → (All below)

Wednesdays – 3pm – Group Meetings (new time)

$\mathcal{M} \to$ varying (from sim), $G_0 = 1$

5 kpc | 15 kpc

(1.2)

- T = temp. simulation
- $c_s = \sqrt{K_B T / m_p}$ → $\mathcal{M} = \text{turb}/c_s$ (1.3)
- $T_{mean} = 10k$ → $\lambda_J = \sqrt{\frac{K_B T_{mean}}{m_p}} \Big/ \sqrt{4\pi G\, n_H\, m_p}$
- $Z = 1$
- $K = 1000\, m_p$ → $n_{LW} = G_0 \cdot \exp \tau$
  - $n_{LW,ss} = G_0 \cdot \exp\tau \cdot S_{H2}$
  - $n_{co} = 10^{-4}\, n_H\, X_{co}$

use c_s from sim.

(1.4)

- T = temp. from sim.
- $c_s = \sqrt{K_B T / m_p}$ → $\mathcal{M} = \text{turb}/c_s$ (1.5)
- $T_{mean} = 10k$ → $\lambda_J = \sqrt{\frac{K_B T_{mean}}{m_p}} \Big/ \sqrt{4\pi G\, n_H\, m_p}$
- $Z \to$ from sim
- $K = 1000\, m_p$ → $n_{LW} = G_0 \cdot \exp\tau$
  - $n_{LW,ss} = G_0 \cdot \exp\tau \cdot S_{H2}$
  - $n_{co} = 10^{-4}\, n_H\, X_{co}$

(1.6) → new version for 1.2

- $Z = 1$
- $K = 1000\, m_p \left(\frac{Z}{0.02}\right)$ → $n_{co} = 10^{-4}\, n_H\, X_{co} \left(\frac{Z}{0.02}\right)$
- $\lambda_J = c_s / \sqrt{4\pi G\, n_H\, m_p}$

new version for 1.3 → (1.7)

(1.8) → new version for 1.4

- $Z \to$ from sim
- $K = 1000\, m_p \left(\frac{Z}{0.02}\right)$ → $n_{co} = 10^{-4}\, n_H\, X_{co} \left(\frac{Z}{0.02}\right)$
- $\lambda_J = c_s / \sqrt{4\pi G\, n_H\, m_p}$

new version for 1.5 → (1.9)

wrong coz units of Z

Reference Plots:

$\mathcal{M} = (10^{-2}, 10^{3})$

$Z = (10^{-2}, 10^{3})$

$G_0 = (10^{-1}, 10^{3})$

$\overline{n_H} = (10^{-5}, 10^{4})$

$T_{mean} = 10\,K$

$c_s = \sqrt{K_B T_{mean}/m_p}$

$\lambda_J = \sqrt{\frac{K_B T_{mean}}{m_p}} \Big/ \sqrt{4\pi G n_H m_p}$

$K = 1000\, m_p \left(\frac{Z}{0.02}\right) \rightarrow n_{CO} = 10^{-4} n_H X_{CO} * \left(\frac{Z}{0.02}\right)$

when $\mathcal{M} = 10^{-2} \rightarrow 10^{3}$, $Z = 1$, $G_0 = 1$
when $Z = 10^{-2} \rightarrow 10^{3}$, $\mathcal{M} = 10$, $G_0 = 1$
when $G_0 = 10^{-1} \rightarrow 10^{3}$, $\mathcal{M} = 10$, $Z = 1$

- Check units of Z !!

- If Z_{mean} accumulates around 0.02 → then it's in solar units
otherwise - mass fraction

For Ref. plots:
- If $Z \rightarrow$ solar ; $Z \rightarrow$ mass fraction
$Z = (10^{-3}, 10)$; $Z = (10^{-4}, 10^{-1})$

- If $Z \rightarrow$ solar ; $Z \rightarrow$ mass fraction
$K = 1000\, m_p \left(\frac{Z}{1}\right)$; $K = 1000\, m_p \left(\frac{Z}{0.02}\right)$

"If the units are in solar units, like "1" meaning "1 Solar units", then the metallicity of the simulation you need to divide by 0.02, & then you send this to your code."
Simulation → is in mass-fraction units.

Simulation ⇒ "Mass Fraction units"

Sub-grid Code

if ~~code~~ $Z_\odot$, then, $Z_{code} = \frac{Z_{sim}}{0.02}$

Z_{code}

$\Rightarrow Z_{code} = (10^{-3}, 10)$

if $Z_{code} \rightarrow Z_{mass\ Frac.}$, then, $Z_{code} = Z_{sim}$

$\Rightarrow Z_{code} = (10^{-4}, 10^{-1})$

1 Mass Fraction (MF) → 0.02 ~~Z~~ Sol

∴ $\boxed{1\ MF = 0.02\ Sol}$

∴ $\boxed{1\ Sol = \frac{1\ MF}{0.02}}$

10 Sol → $10 \times 0.02 = 0.2$ MF

1 Sol → $1 \times 0.02 = 0.02$ MF

⇒ When using simulation Z, divide by 0.02

"mass fraction" units

Version

2.0 → $Z_{code} = \frac{Z_{sim}}{0.02}$ ~~0.02~~ ⇒ Z_{arr}

will be in Solar units

→ And then send this $Z = Z\_arr[m]$ to ~~all~~ everywhere.

Scanned by CamScanner

18/04/19 $Z_{sim} = [\,] \rightarrow$ is in mass fraction

① If I want Z = in mass fraction

then, $Z\_arr = Z_{sim}$

$$K = 1000\, m_p \left(\frac{Z_{arr}}{0.02}\right)$$

$$n_{co} = 10^{-4}\, n_H\, X_{co} \left(\frac{Z_{arr}}{0.02}\right)$$

② If I want Z = in $Z_\odot$

then, $Z\_arr = Z_{sim}/0.02$

$$K = 1000\, m_p\, (Z_{arr})$$

$$n_{co} = 10^{-4}\, n_H\, X_{co}\, (Z_{arr})$$

23|04|2019

→ Correct the colour scheme in the reference plots
→ Print the reference plots in Portrait instead of Landscape.
→ Plot 2.4 & 2.5, if they are correct ~~[illegible]~~ submit jobs for 2.6 & 2.7.
→ Keep the plotting for 2.6 & 2.7 ready after plotting 2.4 & 2.5
→ Prepare introduction & some plots for tanu's group meeting.

Email ① to Anna Troller & cc Prof. Teyssier – Masters Defence room & procedure & last date & how much time before should I email/apply

Email ② to A ______________ – Degree finish in ~~[illegible]~~ August, procedure क्या है?

25/04/2019

→ Differences b/w 1.4.py & 2.8.py:

① main():

~~path = "bulk1/data2/hydro_59/output/"~~

(i) declaring variables outside the main loop instead of declaring them with every iteration of the loop as in 1.4.

(ii) Sending these variables to the inside_loop() function

(iii) $Zarr = Z_{sim}/0.02$

② inside_loop():

(i) re-initialising these variables to zero

(ii) sending m_p to every function.

(iii) Using Zarr without re-dividing by 0.02 in $n_{cw}, n_{cross}, X_{H2}, n_{co}$

→ Ways to find bug: 2.8

① declare variables inside the inside_loop() function – this will be slower & more memory consuming, but will prevent the uncertainity of error in reinitialisation. Also, declare G, m_p, K_b inside inside_loop() & send it to every function. 2.9

② Change $c_s = \sqrt{K_b T_{mean}/m_p}$ instead of $c_{s,arr} = \sqrt{K_b T/m_p}$ 3.0 to see if there is any diff.

3.1 2.8+3.0

③

④ Use $c_s = \sqrt{\gamma P/\rho}$ & see if it makes any diff. 3.3

⑤ ①+④ 3.4

⑥ Make a loop to **single-out all the** "outliers" in the plots — can be done in the plotting_scripts notebooks.

$\bar{X}_{H2}, \bar{X}_{CO}, \bar{n}_H, M, Z$ → load from .npy files saved by scripts 2.8.py to 3.3 py

ctr1 = 0 ; ~~H2_outliers~~ X_H2_out = [ ] ; ~~CO_outliers~~ X_CO_out = [ ] ;
ctr2 = 0 n_H_H2_out
for i in (0, len $\bar{X}_{H2}$) : n_H_CO_out

```
    if n̄_H[i] < 1e-2 && X̄_H2[i] > 0.2 && M[i] < 1e0 :
        X_H2_out[i] == X̄_H2[i], M_H2_out[i] == M[i]
                                n_H_H2_out (i) == n̄_H[i]
        ctr1 += 1

    if n̄_H[i] < 1e0 && X̄_CO[i] > 0.2 && M[i] < 1e0 :
        X_CO_out[i] == X̄_CO[i], M_CO_out (i) == M[i]
                                n_H_CO_out (i) == n̄_H[i]
        ctr2 += 1


CO_outliers = np.array(CO_outliers)
H2 _ _ _ _______________
```

---

① outside loop — 2.8
② inside loop — 2.9

$c_s = \sqrt{\frac{K_B T_{sim}}{m_p}}$

③ $c_s = \sqrt{K_B T_{mean}/m_p}$

④ $c_s = \sqrt{\gamma P/\rho}$

~~2.8 + 3.0 = 3.2~~
~~2.9 + 3.0 = 3.3~~
~~2.8 + 3.1 = 3.4~~
~~2.9 + 3.1 = 3.5~~

2.8 + ③ = 3.0
2.9 + ③ = 3.1
2.8 + ④ = 3.2
2.9 + ④ = 3.3

2.8 — 1679056, 07:20 pm, 25/04/19 ✓
2.9 — 1679318, 11:45pm, 28/04/19
3.0 — 1679057 ✓
3.1 — 1679320, 12am 29/04/19
3.2 — 1679059 ✓
3.3 — 1679321, 12 am 29/04/19

02/05/2019

→ Something up with c_s?

If there is,

$$c_s = \sqrt{\frac{k_B T}{m_p}}$$

T ~~cannot~~ be less than 10 K

If $T < 10K$, (like -ive), fix $T = 10K$

$\therefore c_{s,min} \equiv c_s(T=10K)$

$s[\ \ M\ \ ][\ \ s\text{ values}\ \ ] \Rightarrow s["10.1"]["0, 1, 2, 3, \ldots, 99"]$

(I) turbulence = from simulation [cm/s]

$T_{sim} \to$ from simulation

$$C_s = \sqrt{\frac{K_b T_{sim}}{m_p}} \quad [cm/s]$$

$T_{min} = 12\ K$

$T_{max} = 3 \times 10^8\ K$

$\mathcal{M}$ = turbulence / c_s [1]

$\mathcal{M}_{min} = 0.03$

$\mathcal{M}_{max} = 277$

Plotting $\overline{X}_{H2}$ vs $\overline{n}_H \to$ Image-1

(II) turbulence = from simulation [cm/s]

$T_{mean} = 10\ K$

$$C_s = \sqrt{\frac{K_b T_{mean}}{m_p}} \quad [cm/s]$$

$\mathcal{M}$ = turbulence / c_s

Plotting $\overline{X}_{H2}$ vs $\overline{n}_H \to$ Image-2

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03/05/2019

HII forms from HI

Right now I am assuming that HI is everywhere, which is not true.

Bounds on HI :

- HI is there only if $T \not< 10^4 K$, & $\overline{n}_H > 10^2 [H]/cc$

So when $T > 10^4 K$ or $\overline{n}_H < 10^2 [H]/cc$ ~~[illegible]~~

$\downarrow$ HI is collisionally dissociated

$\downarrow$ HI is not dense enough, so it's photo-dissociated

$\rightarrow$ HII won't form

So when $T \not> 10^4 K$ or $\overline{n}_H < 10^2 [H]/cc$

$X_{H2} = 0$

$X_{CO} = 0$

— Don't touch the formulae for the $\mathcal{M}$, c_s, λ_J, etc.

Just put an 'if' statement on X_{H2} & X_{CO}

$M, Z, \bar{n}_H, G_0, T, c_s$

↳ inside_loop($M, \bar{n}_H, Z, G_0, c_s, T, m_p, s$, pdf, $\lambda_J, X_{co}, n_{co}, \ldots$)

inside_loop(—) :

s = —

n_H = —

pdf = —

λ_J = —

$n_{H2}, X_{H2}, n_{LW}, n_{LW,ss}, X_{H2,ss}, n_{H2,ss}$ = self-shielding-iterations($n_H, G_0, Z, T, m_p, \lambda_J$)

$\bar{n}_H$

self-shielding-iterations() :

if $T \geq 10^4$ || $n_H < 10^2$:

$X_{H2} = 0$ | $n_{LW} = 0$ | $n_{H2} = 0$

$X_{H2,ss} = 0$ | $n_{LW,ss} = 0$ | $n_{H2,ss} = 0$

else

ctr = 16

i = 0

return —

- New Reference Plots
- ~~Jupyter backup~~
- Presentation for Wednesday
- ~~G_0 from Italian Guys' Paper~~
- CO emission spectrum
- PDF Evolution
- Thesis Writing
- Thesis Presentation

- Email Anna Trolles
  reminder
- [illegible]
- Meet Lucio
- Meet Ben Moore

→ PPT

① ~~Title~~

② What I am doing – Basically the Abstract] 2:30 – 3:00

③ Why I am doing – Basically the starting of the introduction
└ 3:30 – 4:30

④ How – Model Outline – 5:00 – 7:00

- ~~PDF~~
- ~~n_H & not f~~
- ~~λ_J (why also)~~ → ~~show the equilibrium eqn. from which n_{LW} is derived~~
- n_{LW}, X_{H2}, n_{H2}, X_{CO}, n_{CO} → ~~Show old plots without ss~~ → ~~remake~~
- self-shielding – $n_{LW,ss}$; $X_{H2,ss}$, $n_{H2,ss}$ → remake → ~~Show new plots with ss~~
  - └ mention Draine's formula
  - └ possibly add a gif to illustrate the movement of $X_{H2,ss}$ from right to left → new
  - (if time allows)
- X_{CO}, n_{CO} – still use n_{LW} & not $n_{LW,ss}$
- $\bar{X}_{H2}$ & $\bar{X}_{CO}$ → formula
  - └ diff. b/w $\bar{X}_{H2}$, $\bar{X}_{CO}$ & X_{H2}, X_{CO}

⑤ Results – 7:00 – 8:00

- Reference Plots ($\mathcal{M}$, Z, G_0, T) → make new
- PDF – $\mathcal{M}$ dependence (log & non-log plots) → remake → in the end
- $\bar{X}_{H2}$ vs $\bar{n}_H$ – $\mathcal{M}$, Z, T (15 kpc) → new
- $\bar{X}_{CO}$ vs $\bar{n}_H$ – $\mathcal{M}$, Z, T (15 kpc) → new
- ~~Both of the above in a single slide~~
- M_{H2}, M_{CO} & M_{ref}.
- Z_{H2}, Z_{CO} & Z_{ref}
- T_{H2}, T_{CO} & T_{ref} → new
- Galaxy maps, X_{H2} & $\bar{X}_{CO}$ → (15 kpc)

The "HOW" Part :

→ ~~Explain in figures only~~
→ ~~Keep slides at the end that show~~
~~→ the formulae for all values~~

→ Just show the formulae – explanation in speaking
→ Start by showing the formulae for each variable one by one – & in when the next variable comes, the previous one scales back to a "normal size".

Eg :

① $\boxed{pdf = \text{---}\exp()}$

② – pdf
$\boxed{n_H = \overline{n}_H \exp(s)}$

③ – pdf
– n_H
$\boxed{\lambda_J = c_s/\sqrt{\rho}}$

④ – pdf
– n_H
– λ_J
$\boxed{\text{solving the equil. eqn:}}$

⑤ – pdf
– n_H
– λ_J
– n_{LW}
$\boxed{X_{H2} = w/o \text{ SS}}$

& so – on.

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→ ~~Make all plots~~
→ ~~Make new reference sheet~~
→ ~~Paste all plots in the ppt~~

→ ~~Listen to Meeting recording~~
→ ~~Write the Explanation Romain says~~
→ ~~Add that explanation in the slides~~
→ ~~Add the equation of equil. for $n_{i,w}$.~~
→ ~~Add the formulae for all variables~~

~~Morning~~;
→ ~~Print both reference sheets~~
→ ~~Give the sheets to Prof Teyssier~~
→ ~~Ask Michael about the Galaxy map that isn't plotting~~

→ ~~Why X_{H2} & X_{CO} plots have to be different~~
→ ~~What is self shielding~~
→ Diff. b/w $\bar{X}_{H2}$ & X_{H2} / $\bar{X}_{CO}$ & X_{CO}
→ Why is G_0 constant in simulation?
→ How M, Z, T affect $\bar{X}_{H2}$ / $\bar{X}_{CO}$ ~~plots~~ ??
→ ~~Prof. Teyssier Explanation in the prev. group meeting~~

→ the width is because of diff. values of these parameters.

Presentation on 08/05/19
→ Group Meeting

$\rightarrow$ 5kpc

08|05|2019

(No rec.; surprise meeting)

Session - 3.8

→ The temp. from the simulation is a bit weird

→ T is related to density ρ, so at high ρ,

$T \sim 10K$

→ <u>TASK</u> :- Plot all the sim. plots by keeping $T = 10K$

i.e; c_s = fixed. → for sub-grid

$\therefore \lambda_J = c_s / \sqrt{\rho}$

- For $\mathcal{M}$, $T = T_{cell} = T_{sim}$,

$\therefore \mathcal{M} = \frac{\sigma_v}{c_s(T_{sim})}$ → not fixed → for sim.

if $T >= 10^4$ / $\overline{n_H} < 10^{-2}$

$X_{H2} = \overline{X}_{H2} = X_{CO} = \overline{X}_{CO} = 0$

13|05|2019

Meeting ...

The Blac...

plots from...

(H2) → ...

Solution: ...

For the S...

① Check...

② Fix ...

& ...

③ Fix ...

(3.9)

& ...

④ $\mathcal{M} =$ ...

⑤ $\mathcal{M} =$ ...

13/05/2019

Meeting with Prof. Teyssier + Robert Feldmann

The Black line from reference plots do not match the plots from simulation.

(H2) → At $\bar{x}_{H2} = 0.5$, ~~the~~ & $M = 10$ → ref. plots, the $\log \bar{n}_H \sim 1$

But in simulation, even though the colouring shows that most of $M \sim 10$, $\log \bar{n}_H \neq 1$ for most. Actually, at $\bar{x}_{H2} = 0.5$ & $M = 10$, $\log \bar{n}_H$ should be 1, but it's shifted on the left too much.

Solution:

For the Sim. plots

① Check colouring for M → only one $\bar{x}_{H2}$ pt. → not possible

② Fix $M = 10$, $Z = 1$ solar, $G_0 = 1$, $T = 10K$

$C_s = C_s(\bar{T} = 10K)$, $M = 10$ (fixed)

& then plot

↳ the plot should be the same as black line in the ref. plots. ~~[illegible]~~

③ Fix $M = 10$, Z = varied → simulation, $G_0 = 1$, $T = 10K$

$C_s = C_s(\bar{T} = 10K)$, $M = 10$ (fixed)

3.9 & then plot

↳ the plot should be the same as black line in the varied-Z ref. plots.

④ $M = M(T = T_{sim})$, Z = varied, $G_0 = 1$

$C_s = C_s(\bar{T} = 10K)$, M = varied ⇒ $M(T_{sim})$ → 3.8

↳ plot

⑤ $M = M(T = T_{sim})$, Z = varied, $G_0 = 1$

$C_s = C_s(T = T_{sim})$, M = varied ⇒ $M(T_{sim})$ → 3.5

↳ plot

14|05|2019

Line Transfer

$\boxed{\text{Bound - Bound transitions}}$ → resulting from opacities of gas (unlike dust)

→ QM ~~sel~~ selection rules

→ Gas atoms/molecules have discrete energy states

2 types

Collisional Transitions

Atoms/molecules jump from one state to another by colliding with each other.

Radiative Transitions

Atoms/molecules jump from one state to another by sending out or absorbing a photon.

both are discussed

Index:

→ **Quantum states of atoms & molecules:**
- Levels & their occupations: n_i, N_i, N, LTE
- Degenerate states/Statistical weights: E_i, g_i
- Partition Function: $Z(T)$
- Collisional transition: C_{ij} & C_{ji}

→ **Line emission & absorption:**
- Einstein Coefficients: $j_{ij,\nu}, \alpha_{ij,\nu}, A_{ij}, B_{ij}$
- Alternative notation: oscillator strength: f_{ij}, A_{ij}
- Doppler shift: ϕ_{ij} (Line profile intro)
- Selection Rules: $i \to j$
- Lists/Values needed

→ **Examples for Atoms:**
- H & H-like: E_{nlms}, j, l, s, g
- Multi-e^- atoms: $^{2S+1}L_J$, J, g
- Databases available

→ **Examples for Molecules:**
g, J, E for CO, NH_3 (ortho, para also)
- Rotational Lines: g, J, E for CO
- Ro-vibrational Lines: $E_\upsilon, E_{\upsilon J}$ for CO
- Databases available

→ **Line Profile Function:**
- Doppler broadening: Thermal case - sound speed
- Doppler broadening: Turbulence
- Collisional broadening
- Natural broadening
- Lorentz + Gauss = Voigt profile

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- Case of LTE :
  - Intro
  - Integrated line spectrum from a disk
  - Examples of diff. obsewations : P- Cygni & inverse P-Cygni

- Case of Non-LTE + optically thin :
  - Intro
  - Equations

- Case of Full Non-LTE :
  - Equations
  - Assumptions

- Lambda Iteration for line transfer :
  - Intro
  - Equations

- Accelerated Lambda Iteration (ALI) method - Rybicki :
  - Intro
  - Equations

- Line "scattering" in a 2-level atom

- Photon Escape Probability & Escape probability method :
  - Intro
  - Formulism
  - Eqn.s

- Large Velocity Gradient (LVG) method - Sobolev

- Some common line RT phenomenon

⊛ Quantum State of Atoms & Molecules :

→ Levels & their occupations :

N_{levels} → no. of energy states/levels of an atom/molecules

∴ $i \to 1, \ldots, N_{levels}$ → Ascending order

∴ $E_i > E_{i+1}$ → Energy

N_i → Occupation no. ≡ no. of atoms/molecules in a particular (ith) Energy level/state

$N \equiv \sum N_i$ ≡ total no. of atoms ~~molecules~~ or molecules /cm³

$n_i \equiv$ Fractional Occupation no. $\equiv \frac{N_i}{N} = \frac{N_i}{\sum N_i}$ — (1)

↳ $\sum n_i = 1$

⇒ N should be the same quantity as n_{co} in the code.

when collisional transition (CT) ≈ radiative transitions (RT), like in a dense gas cloud, the occupation no.s can be easily calculated using the thermal properties (from collisional) ~~...~~ of the cloud. Then, ∵ CT ≃ RT, we can assume that the occupation no.s from RT will be the same.

If K_B ≡ Boltzmann const. & T ≡ Temp. of the gas, $i \to j$

$$\frac{n_j}{n_i} = \frac{N_j}{N_i} = \exp\left[\frac{-(E_j - E_i)}{K_B T}\right] \quad — (2)$$

This means that CT ≃ RT ⇒ LTE

If CT ≠ RT, eg: in a less dense cloud ⇒ NON-LTE

↳ In this case n_i will not follow (2) ~~...~~

↳ other methods to calc. n_i

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→ Degenerate states & statistical weights :

Usually, $E_{i+1} = E_i$

This is because of rotational symmetry.

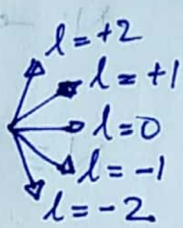
Eg: For an H-atom → wave-function ψ_{lm}

l → total ang. momentum of the atom/molecule

m → denotes angular orientations

$l = 0, 1, 2, \ldots$

$m = -l, \ldots, +l$



So diff. 'm' states will have diff. energies because they have different orientations

↳ w.r.t. to what?

to an ext. elec./mag. field

So if there is no ext. elec./mag field, all states will have ~~the~~ same energy; which means that all these states ~~[illegible]~~ are basically the same state with multiple occurences ⇒ degeneracy

↳ given by statistical weight (g_i)

For an e^-, $g_i = 2l+1$ (Here, l = orbital ang. mom. of the e^- in state i)

Putting this concept in eqn. (2) :

$i \rightarrow j$

$$\frac{n_j}{n_i} = \frac{N_j}{N_i} = \frac{g_j}{g_i} \exp\left[-\frac{(E_j - E_i)}{K_B T}\right] \quad - (3)$$

→ Partition Function :

Eqn. ③ gives the ratio n_j/n_i, but not n_i itself.
So to find n_i :

Partition Function $\equiv Z(T) = \sum g_i \exp\left[\frac{-E_i}{K_B T}\right]$ — ④

↳ A function of temperature
↳ Summing over ALL states

Then ;

$$n_i = \frac{1}{Z(T)} g_i \exp\left[\frac{-E_i}{K_B T}\right] \quad — ⑤$$

↳ in LTE
↳ Z(T) is basically the "normalisation const." here

→ Collisional Transition b/w levels :

∵ Atoms/molecules are in constant motion, they can change their energy state after collisions

The rate (= events per second) by which an atom/molecule in state 'i' is collisionally changed to state 'j' is : $C \equiv [\#/sec]$

$$C_{i\to j} \equiv C_{ij} = N K_{i\to j}(T) \equiv N K_{ij}(T)$$

$N \equiv$ Total no. density [#/cc] of possible colliding particles
↳ ($\equiv n_{co}$??)

$K_{ij} \equiv$ Collision Coefficient
↳ Already calculated in databases for most atomic/molecular species

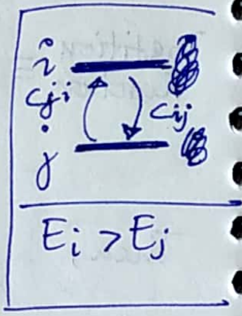
But now let's say $E_j < E_i$, and we know that there is a temp. dependence of K_{ij} (a weak temp. dependence, but it's there). Then we can get C_{ji} & C_{ij} by assuming that the upward & downward collision rates are the same, i.e., LTE.

This means that :

$$n_j C_{ji} = n_i C_{ij} \quad - ⑥ \quad \left\{ n_j C_{j \to i} = n_i C_{i \to j} \right\}$$

Putting in ③,

$$C_{ji} = C_{ij} \frac{g_i}{g_j} \exp\left[-\frac{(E_i - E_j)}{K_B T} \right] \quad - ⑦$$



In general tho, molecules have different collision partners.

Eg: A CO molecule in ISM will more likely be hit by a H_2 molecule than another CO molecule.

So, 2 or more collision partners are important.

Line Emission & Absorption :

→ Einstein Coefficients :

$$\cancel{\frac{dI_\sigma}{dx} = -N_\sigma I_\sigma + j_\sigma}$$

absorption coeff. α_υ

$$\frac{dI_\sigma}{dx} = -\alpha_\sigma \cdot I_\sigma + \alpha_\sigma \cdot B_\sigma(T)$$

$$\frac{dI_\upsilon}{dx} = -\alpha_\upsilon \cdot I_\upsilon + \alpha_\upsilon \cdot S_\upsilon(T)$$

$$IF = e^{-\int_1^2 d\tau} = e^{-(\tau_2-\tau_1)}$$

$$\frac{dI_\upsilon}{d\tau_\upsilon} = -I_\upsilon + S_\upsilon(T)$$

$$e^{-(\tau_2-\tau_1)} \frac{dI_\upsilon}{d\tau_\upsilon} = (-I_\upsilon + S_\upsilon)\, e^{-(\tau_2-\tau_1)}$$

$$e^{-(\tau_2-\tau_1)} \frac{dI_\upsilon}{d\tau_\upsilon} + I_\upsilon e^{-(\tau_2-\tau_1)} = S_\upsilon e^{-(\tau_2-\tau_1)}$$

$$\frac{d}{d\tau_\upsilon}\left[e^{-(\tau_2-\tau_1)} I_\upsilon\right] = \left[\frac{d}{d\tau_\upsilon}\left(e^{-(\tau_2-\tau_1)}\right)\right] S_\upsilon$$

$$I_\upsilon \cdot e^{\tau_2-\tau_1} = \int_1^2 S_\upsilon e^{\tau_\upsilon}\, d\tau_\upsilon$$

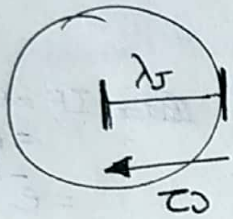
$$I_\upsilon \cdot e^{\tau_2-\tau_1} = S_\upsilon e^{\tau_2-\tau_1}$$

$$I_\upsilon = I_{\upsilon,0} \cdot e^{-(\tau_2-\tau_1)} + B_\upsilon\left(1 - e^{-(\tau_2-\tau_1)}\right)$$

$$I_\nu = I_{\nu,0}\, e^{-(\tau_2-\tau_1)} + B_\nu \left(1 - e^{-(\tau_2-\tau_1)}\right)$$

~~rad field LTE~~

$$I_\nu[i][j] = I_{\nu,0}[i][j] \cdot \exp[-(\tau[i][j+1] - \tau[i][j])]$$
$$+ B_\nu[i][j]\left(1 - \exp[-(\tau[i][j+1] - \tau[i][j])]\right)$$



$$\frac{\cancel{eV}\cdot\cancel{s}}{s\cdot cm^3\, \cancel{eV}\cdot\cancel{s}}$$

$$\cancel{eV}\cdot\cancel{s} \cdot \frac{1}{s} \cdot \frac{1}{cm^3} \cdot \frac{\cancel{cm^2}}{\cancel{eV}\cdot\cancel{s}}$$

loops i, j :

] computations

$$eV\cdot\cancel{s} \cdot \frac{1}{\cancel{s}} \cdot \frac{1}{cm^3} \cdot \frac{1}{s}$$

$$\frac{eV}{cm^3\, s}$$

n_H, n_{CO}, n_{H2}, $\lambda_J \rightarrow$ len = 100

$\downarrow$

100×41

1 cell

Level 2 $\rightarrow$ Level 1 $\quad i-1 \rightarrow j-1$

$E_i = 4.7\times10^{-3}$ eV	$g_i = 3$	$\nu_{ij} = 115.27$ GHz
$E_j = 0$ eV	$g_j = 1$	$\nu_{ji} = 115.27$ GHz

$A_{ij} = 7.203\times10^{-8}$

$B_{ij} = 5.12\times10^{-10}$

$B_{ji} = 1.533\times10^{-9}$

$C_{ij} = 3.3\times10^{-17}$

$C_{ji} = 3.80\times10^{-17}$

$\alpha = h\nu$

LTE :

```
i = 0
j = 0
while i < num_lvls :
    while j < num_lvls :
        if freq [i][j] != 0.0 :
            Source_func [i][j] = B_nu_ev(freq[i][j], T̄)
            α_ν[i][j] = ___
            jν[i][j] = α_ν[i][j] * Sν[i][j]
            τ_ν[i][j] = ___
            β[i][j] = ___
            I_ν,bg = B_ν(T_CMB)
```

$$\frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu$$

TE : $I_\nu = S_\nu = B_\nu(\bar{T}) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/KT} - 1}$; $\bar{T} = 10K$

LTE : $S_\nu = B_\nu(\bar{T})$

$I_\nu \neq B_\nu(\bar{T})$

solving $\frac{dI_\nu}{d\tau_\nu} = I_\nu - B_\nu(T)$

$\hookrightarrow I_\nu = I_{\nu,0}\, e^{-\Delta\tau} + B_\nu(1 - e^{-\Delta\tau})$

$I_\nu = I_{\nu,0}\, e^{-(\tau_\nu - \tau_{\nu,0})} + B_\nu(1 - e^{-(\tau_\nu - \tau_{\nu,0})})$

$\Delta\tau = \int$ — which length scale to integrate over?

SONIC LENGTH ?

91, 127, 347

$\boxed{\text{James Jeans (Jeans, 1902)}}$ → Paper For "Jeans Length"

Molecular Cloud

→ Mass measurement :

^{12}CO, ^{13}CO, & recently, HCN

^{12}CO ↓ optically thick lines

^{13}CO ↓ optically thin lines ↓ simplest

RTE : $I_\nu = (1 - e^{-\tau_\nu}) B_\nu(T)$

I_ν ↑ intensity emitted by cloud

$B_\nu(T)$ ↑ Planck f" at ν & T

For ^{13}CO :

If N_{co} = column density of ^{13}CO atoms, then at LTE, the column densities of atoms in the levels 0 & 1 states are :

$$N_0 = \frac{N_{co}}{Z}$$

$$N_1 = \frac{N_{co}}{Z} \cdot \exp\left(-\frac{T}{T_1}\right)$$

$Z \equiv$ Partition function

$T_1 = 5 \cdot 3K$ ← temp. corresponding to the 1st excited state

then, Opacity to line absorption :

(extinction) → $K_\nu = \frac{h\nu}{4\pi}(n_0 B_{01} - n_1 B_{10}) \phi(\nu)$ ← line shape function

~~emission~~

B_{01} = spont. absorption = $\frac{g_1}{g_0} B_{10}$

B_{10} = stimulated emission $= \frac{c^2}{2h\nu^3} A_{10}$

Then, optical depth at line-centre is :

$$\tau_\nu = \frac{h\nu}{4\pi}(N_0 B_{01} - N_1 B_{10})\phi(\nu)$$

For an optically thin line, the width of the line is determined primarily by the velocity distributⁿ of the emitting molecules.

$\psi(v) \equiv$ gas vel. distri.

i.e., the fraction of gas with velocities b/w v & $(v+dv)$ $= \psi(v)\,dv$

& $\int_{-\infty}^{\infty} \psi(v)\,dv = 1$

Here, natural & pressure-broadening of lines is negligible, which is almost always the case when observing the cold-dense-ISM

And, we can think of emission producing a delta-function in frequency in the rest frame of the gas.

↳ & there is one-to-one mapping b/w v & ν

∴ Emission from gas moving at v relative to us along our line of sight produces emission at a frequency $\nu \simeq \nu_0 \left(1 - \frac{v}{c}\right)$

central freq. of molecule in rest frame

& we assume $\frac{v}{c} << 1$

∴ line profile in this case, $\phi(\nu) = \psi * \left[c\left(1 - \frac{\nu}{\nu_0}\right)\right]$

$$\phi(\nu) = \frac{c}{\varsigma_s \nu_i \sqrt{\pi}} \exp\left[-\frac{c^2(\nu-\nu_i)^2}{a^2 \nu_i^2}\right]$$

Consider
Turbulent medium with linewidth-size relation.

"Star Formation" book by Mark Krumholz

$$\sigma(\ell) = c_s \left(\frac{\ell}{\lambda_s}\right)^{1/2}$$

sonic length

$$\alpha_{vir} = \frac{5\sigma^2}{G\rho R^2} = \frac{5\sigma^2}{G n_H m_p R^2}$$

$\alpha_{vir} = \boxed{\sim 1}$

if $R = \lambda_J$, can we get $\sigma(\lambda_J)$? vel. disp.

After σ, $\sigma(\lambda_J) = c_s \left(\frac{\lambda_J}{\lambda_s}\right)^{1/2}$

can we get λ_s

if $\lambda_J = \sqrt{\frac{c_s^2}{G n_H m_p}}$; $\bar{\lambda}_J = \sqrt{\frac{c_s^2}{G \bar{n}_H m_p}}$

$$s = \ln(\rho/\bar{\rho}) = \ln(n_H/\bar{n}_H)$$

$$s_{crit} = \ln(n_{crit}/\bar{n}_H)$$

then, $s_{crit} = \left(\frac{\bar{\lambda}_J}{\lambda_s}\right)^2 \simeq \alpha_{vir} \mathcal{M}^2$ mach no.

$$\lambda_J = \frac{c_s}{\sqrt{4\pi G n_H m_p}}$$

$\therefore$ ~~$\lambda_J^2 = \frac{c_s^2}{4\pi G n_H m_p}$~~ $\Rightarrow c_s = \sqrt{4\pi G n_H m_p \lambda_J^2}$

RTE : $\dfrac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu$

① Thermal Equilibrium (TE) :

$$I_\nu = S_\nu = B_\nu(\bar{T}) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{K_B \bar{T}}\right) - 1} \quad ; \quad \bar{T} = 10\,K$$

② Local Thermodynamic Equil. (LTE) :

$$S_\nu = B_\nu(\bar{T}) \qquad \bar{T} = 10\,K$$

$$I_\nu \neq B_\nu(T)$$

Solving RTE for I_ν :

$$\left[I_\nu = I_{\nu,bg} \cdot \exp(-\tau_\nu) + B_\nu(\bar{T})\left(1 - \exp(-\tau_\nu)\right) \right]$$

$$\tau_\nu = \frac{hc}{4\pi} N_i \left(n_j B_{ji} - n_i B_{ij}\right) \times \frac{1}{1.064 \cdot grad\_v}$$ [From Tine's code]

$$grad\_v = c_s = \sqrt{\frac{K_B \bar{T}}{m_p}}$$

n_i, n_j = Fractional occ. no. $= \dfrac{g_i \exp(-E_i/K_B \bar{T})}{Z(T)}$

$N_i, N_j = n_i * N$

$N = n_{co}[0]$ ← [From sub_grid : n_{co} → array of 100 values]

$$I_{\nu,bg} = B_\nu(T_{bg}) \quad ; \quad T_{bg} = T_{CMB} = 2.73\,K$$

Optically thin medium : $\tau_\nu \ll 1 \Rightarrow B_\nu(1 - e^{-\tau_\nu}) \simeq B_\nu \tau_\nu$

③ Non-LTE

For Sonic length :

$$\alpha_{vir} = \frac{5\sigma^2}{G n_H m_p R^2}$$

we know $\alpha_{vir} \simeq 1$

putting $R = \lambda_J$

then, $\sigma(\lambda_J) = \sqrt{\frac{G n_H m_p \lambda_J^2 \alpha_{vir}}{5}}$

Now, linewidth-size relation :

$$\sigma(\lambda_J) = c_s \left(\frac{\lambda_J}{\lambda_s}\right)^{1/2} \quad ; \lambda_s \equiv \text{sonic length}$$

$$\therefore \lambda_s = \frac{\lambda_J c_s^2}{\sigma(\lambda_J)^2}$$

Now, $\lambda_J = \sqrt{\frac{c_s^2}{G n_H m_p}}$; $\overline{\lambda_J} = \sqrt{\frac{c_s^2}{G \overline{n_H} m_p}}$

$$s = \ln\left(\frac{n_H}{\overline{n_H}}\right) \quad ; \quad s_{crit} = \ln\left(\frac{n_{H,crit}}{\overline{n_H}}\right)$$

then, $s_{crit} = \left(\frac{\overline{\lambda_J}}{\lambda_s}\right)^2 \simeq \alpha_{vir} \mathcal{M}^2$ mach no.

22|05|2019

To fit the $\overline{X}_{H2}$ graph :

→ It'll take ~min.s instead of ~hours to run & will definitely save time.

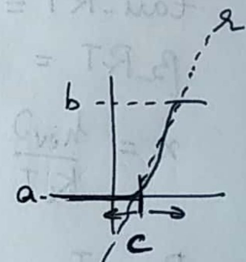
Logistic Function is the one I need : (Sigmoid Functions)

eg: $$P(t) = \frac{K P_0 e^{rt}}{K + P_0(e^{rt} - 1)}$$

Let:

$K = b - a$ | a → control the lower pt. of f''

$P_0 = \frac{b-a}{2}$ | b → control the upper pt. of f''



$t = x - c$ → to control the step location

r term → controls the slope

The f'' becomes :

$$\boxed{f(x) = \frac{\frac{(b-a)^2}{2} \cdot e^{r(x-c)}}{(b-a) + \left(\frac{b-a}{2}\right)\left(e^{r(x-c)} - 1\right)} + a}$$

$$\therefore f(x) = \frac{a \cdot e^{cr} + b \cdot e^{rx}}{e^{cr} + e^{rx}}$$

$b = 1, \ a = 0$

$$\therefore f(x) = \frac{\frac{1}{2} \cdot e^{r(x-c)}}{1 + \frac{1}{2}\left(e^{r(x-c)} - 1\right)} = \frac{e^{r(x-c)}}{e^{r(x-c)} + 1}$$

$r \to M$ | $x \to \log 10 (\bar{n}_H)$

$c \to Z, G_0$ | $f(x) \to \overline{X}_{H2}, \overline{X}_{CO}$

28/5/19

freq = from file = GHz → Hz

E = from file = $cm^{-1} \to eV$

A = from file = s^{-1}

$$B_{ij} = \frac{A_{ij} c^2}{2 h \nu_{ij}^3} = \frac{cm^2}{eV \cdot s}$$

$$\text{grad\_nu} = \frac{c_s \cdot \nu_{ij}}{c} = \frac{1}{s} = Hz$$

tau_RT = [ ]

β_RT = [ ]

$$x = \frac{h_{ev} \nu}{k_b T} = [\,]$$

$$B_\nu, I_\nu, S_\nu = \frac{eV}{cm^2} \text{ or } \frac{eV}{s \cdot Hz \cdot cm^2}$$

λ_J = cm

c = cm/s

c_s = cm/s

$N = n_{co} = cm^{-3}$

$n_i = [\,]$

$N_i = N \cdot n_i = cm^{-3}$

$T = \bar{T} = 10K$

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

$$n_i = \frac{g_i \exp\left(\frac{-E_i}{k_b T}\right)}{Z} \quad ; \quad Z = \sum g_i \exp\left(\frac{-E_i}{k_b T}\right)$$

$$\text{grad\_nu} = \frac{c_s}{c} \cdot \nu_{ij}$$

$$\text{tau\_RT} = \frac{h_{ev} \nu_{ij} \lambda_J N (n_j B_{ji} - n_i B_{ij})}{4\pi \, \cancel{\text{grad\_nu}} \, \Delta\nu}$$

beta_RT : $\tau < 0.01$: $\beta = 1 - \frac{\tau}{2}$

$\tau > 100$: $\beta = 1/\tau$

otherwise : $\boxed{\beta = \frac{(1 - \exp(-\tau))}{\tau}}$

$$x = \frac{h_{ev} \nu}{k_B T} \Rightarrow B_\nu = \frac{2 h_{ev} \nu^3}{c_{cgs}} \frac{1}{\exp(x) - 1}$$

$I_{\nu,bg} = B_\nu (T = 2.73K)$

$I_\nu = I_{\nu,bg} \cdot \exp(-\tau) + \cancel{B_\nu \cdot \tau}$ $+ B_\nu (1 - \exp(-\tau))$

$$j_\nu = \frac{h_{e\nu} \cdot \nu_{ij} \cdot N \cdot n_i \cdot A_{ij} \cdot \beta}{4\pi} \equiv \frac{eV}{s \cdot cm^3\, sr}$$
emissivity

$$\alpha_\nu = \frac{h_{e\nu} \cdot \nu_{ij} \cdot N \cdot (n_j B_{ji} - n_i B_{ij})}{4\pi} \equiv \frac{1}{cm \cdot sr \cdot s}$$
extinction

$$S_\nu = \frac{j_\nu}{\alpha_\nu} = \frac{\frac{eV}{\cancel{s} \cdot cm^{\cancel{3}2} \cancel{sr}}}{\frac{1}{\cancel{s} \cdot \cancel{cm} \cdot \cancel{sr}}} = \frac{eV}{cm^2}$$

$$\boxed{I_\nu = (1 - \beta_{ij})\, B_\nu + \beta_{ij}\, I_{\nu,bg}}$$

for optically thin/thick

Up → Low ≡ Allowed

Low → up ≡ NOT Allowed

2 → 1
3 → 2
4 → 3
] - Allowed

1 → 2
2 → 3
3 → 4
] - Not Allowed

i → up
j → low

out $i = 0 \to 41$:

in $j = 0 \to 41$:

$i = 0$
$j = \cancel{0}\ 1\ 2$

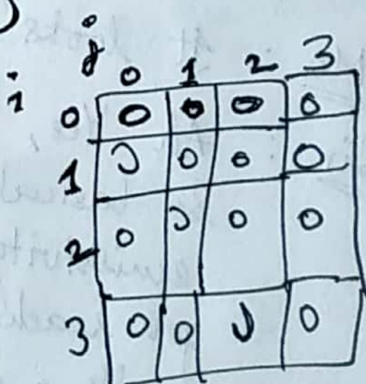
$i > j$:
ctr =

out $i = 0$
iteration = in $j \to \cancel{0} - 41$

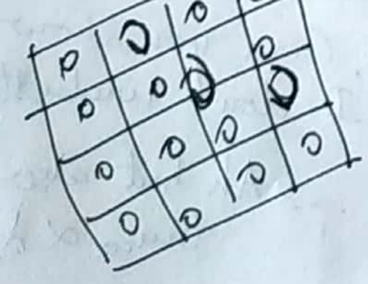
out $i = 1$
in $j = 0 \to 41$
ctr = 1

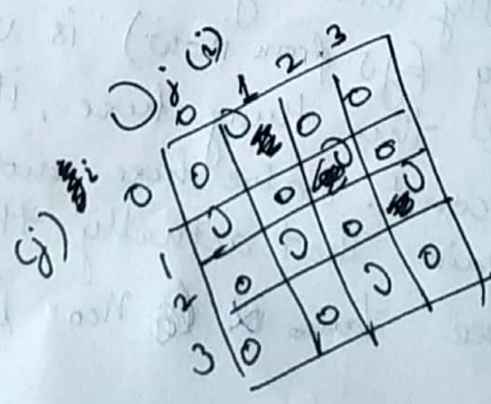
$\left| \begin{matrix} i = 1 \\ j = 0 \end{matrix} \right]$

iteration = $i = 2$
$j =$



$i - j == 1$





Meeting - 3 : 29/05/19 :

{Already plotted β_{co} vs log n_H
log (tau_{co}) vs log n_H }

"So, this is β vs n_H" - Me

Sir : Right; so it's n_H, great, so it seems to.
Do you have X_{co} somewhere so that you can overplot X_{co} vs n_H. Because it should be shifted a little bit.
Yeah, it look fine.

If your plot now...
Because the Luminosity now will be proportional to...
ah... so the Source function here will be $S_\nu = \frac{j_\nu}{\alpha_\nu}$.

what we want is j_ν. Exactly.

$$\text{So } j_\nu = \text{const.}\ \underset{\uparrow\ \text{const.}}{\nu_{ij}}\ \underset{\uparrow\ =n_{co}}{N}\ \underset{\uparrow\ \text{const}}{n_i}\ \underset{\uparrow\ \text{const}}{A_{ij}}\ \beta$$ ← we have

So if you plot $n_{co} * \beta$ vs log (n_H), we can get an approximate idea about j_ν."

"Yes, it looks okay!"

Me : It looks similar to lg(tau_{co}) vs log n_H
It looks similar in a sense.

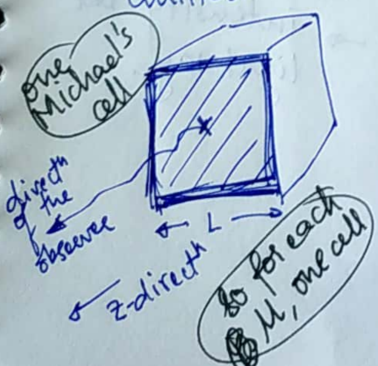
Sir : Ah Yes, that looks similar in a sense. That the
So basically what you see here is that the emissivity (j_ν from now) is very low, & then once you reach this thing here, it saturates. And, it's really a const. value here mostly. Can you show tau_{co} again. That actually that I don't understand.
So you see $tau_{co} \propto n_{co}$ here... Ah but also $tau_{co} \propto \lambda_J$.

& λ_J goes as $\frac{1}{\sqrt{n}}$, so tau $\propto \sqrt{n}$.
Maybe it's because there is too much dynamics here.
Can you zoom into this range: 2 to 6 & +5 to −5"

"Yeah exactly, so we say $\sqrt{n}$ right, so... $\sqrt{n}$ means that if you have 2 orders of magnitude here you should see 1 order of magnitude here... yeah so it's not.... it is it is steadily increasing, right. So you see that β, if tau is large – which is the case here – actually tau is 1 at $n_H \sim 3000$, now for large τ, $\beta \simeq \frac{1}{\tau}$, now $1/\tau$ means $1/\sqrt{n}$
So now when you multiply by n to get the emissivity, so $j\upsilon$, then we get $\sqrt{n}$. So that's normal. ($N = n_{co}$; $c_s \propto 1/\sqrt{\mu m_H}$)
Okay. So now I think that you're ready to compute the emissivity.
The emissivity for each bin:

$$j\upsilon = \frac{h_{ev}\,\upsilon_{ij}}{4\pi}\, n_{co}\, n_i\, A_{ij}\, \beta$$

So in principle, $j\upsilon$ = erg $s^{-1}\, Hz^{-1}\, cm^{-3}$
Now, let's see, you're looking at the galaxy, that's always the key pt.
If you now consider a cubicle cell, the photons are emitted in the direct^n of the observer, & so what will be emitted will be the integral along the z-direct^n (direct^n of observer),



$$\int_0^L j\upsilon \, dz$$

= erg $cm^{-2}\, s^{-1}\, Hz^{-1}$
→ K
Clearly the same unit as black body.

So what people are doing is that they are assimilating erg cm^{-2} s^{-1} Hz^{-1} as Kelvin (K).

If you assume that the tube is a BB, at a given freq. ν, then we have $B_\nu(T)$, & from that we deduce T.

Let's call this I_ν.

Oh BTW, you've to multiply by β.

So, $j_\nu = \frac{h\nu}{4\pi} n_{co} n_i A_{ij} \phi_\nu$ $\qquad \phi_\nu = 1/\Delta\nu = \left(1 / \frac{\xi}{c}\nu_{ij} \right)$

& what comes out of the box is $j_\nu \cdot \beta$

Then this photon won't be absorbed anymore, it'll go directly to the observer. And this is I_ν, the radiation field:

$$\int_0^L \beta j_\nu \, dz = I_\nu$$

→ that's the correct units

So if you say that $I_\nu = B_\nu(T)$ → then you get T.

Or if you want $T = B_\nu^{-1}(I_\nu)$

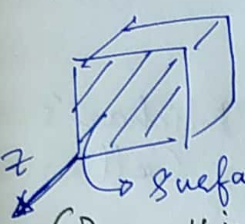
What it means that this I_ν can be expressed in units of Kelvin (K).

Now here is the complication.

$\therefore$ K ↔ erg cm^{-2} s^{-1} Hz^{-1} → intensity per light ray.

So now, this is (Hz^{-1}) (cm^{-2})

↳ basically the surface area in z-direction



(Rem: this is 1 Michael's cell)

Now, if you multiply by the size of this box − L^2

And then you also multiply by a <u>frequency range</u>,

because you integrate along the <u>surface</u>, & you integrate along the <u>freq.</u>, & the <u>freq.</u> is usually expressed in $\boxed{km/sec}$.

in parsecs

$$\therefore \left(erg\ \underline{cm^{-2}}\ s^{-1}\ \underline{Hz^{-1}} \leftrightarrow K\right) \times L^2 \times \text{freq. range}$$

$$\therefore K \cdot \underline{pc^2} \cdot \underline{km/s}$$

↳ so you see that you integrate out the surface & the freq., so you're left with

↳ $\underline{erg\ s^{-1}}$

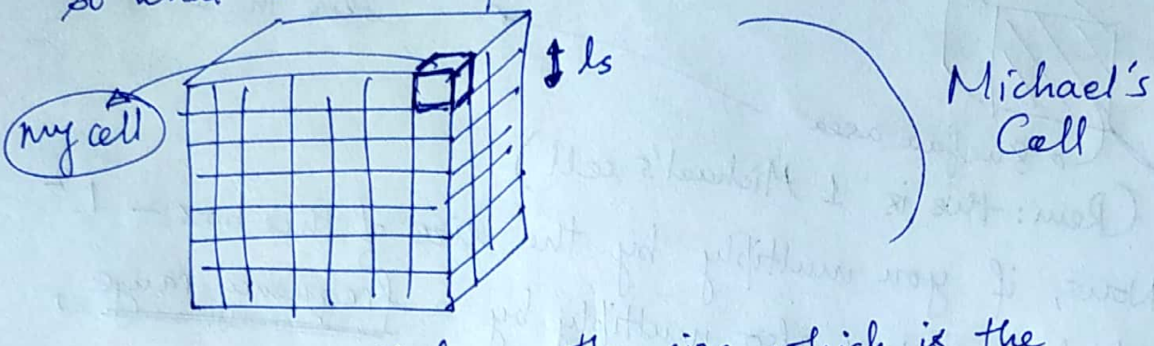
which is the luminosity

L_{CO}

natural units: $erg\ s^{-1}$

astronomical units: $K \cdot pc^2 \cdot km/s$

So, now we have to go back to our pdf.
So what we have for each



Each my-cell has the size which is the sonic length (l_s)

Co [ds, s → something to do with sonic length]

→ And for each one of those you have a given density.
So, in principle, now you've to sum-up the entire Luminosity .... so for each of those guys (my-cell) - you know the density, & you can compute what is the emissivity (j_0) then $B j_0$ & you can integrate over the size of this little guy (my-cell).
And then, what you also know that the total volume of the cell, $V = N_s \cdot V_s$

N_s → no. of those sonic length scale cells
V_s → Volume of each sonic length scale cell

Now when you integrate your pdf, so
$$\int P \, ds = 1$$ → that's the total volume.
Co by doing this you can calc. the total emissivity.

So you know that

$\beta \cdot j_\nu$ = erg cm^{-3} s^{-1} Hz^{-1} → that's what comes out.

So now you can compute what comes out from the entire cell by integrating over the volume.

∴ The Luminosity / unit freq. of the cell will be

$$\underbrace{\int_{cell} \beta j_\nu \cdot \underbrace{dv}_{\text{vol. fraction}}}_{\text{integral over the entire cell}} = \int_{cell} \beta j_\nu \cdot \underline{P.ds} = $$ we get the total emissivity of the cell $= (\overline{\beta j_\nu})$

Now, if you multiply by the length of the cell, you get this I_0,

$$\int_0^L \underbrace{\overline{\beta j_\nu}}_{\text{avg. emissivity integrated over the pdf.}} dz = I_0$$ → for each Michael's cell (each $\mathcal{M}$, one I_0)

That's the computation that you need to do.

~~That's the integrate βj_ν~~

~~So you need to integrate βj_ν~~

Compute βj_ν

then integrate over pdf

then you're gonna get $\overline{\beta j_\nu}$

then integrate of 0 - L dz

then you get I_0

↕

K

$$\Delta v_{turb} = \frac{\sigma_{turb}}{c} \cdot \nu_{ij}$$

Now, for km/sec → multiply with σ_{turb} (from simulation)

for pc^2 → multiply with S.A. of each Michael's cell

$$\left(\int_0^L \overline{\beta j_\nu}\, dz \right) / \Delta v_{turb} \equiv \text{Kelvin}$$

~ a few Kelvins

$$B_0 = \frac{2 h_{ev} \nu_{ij}^3}{c^2} \cdot \frac{1}{\exp\left(\frac{h_{ev}\nu_{ij}}{K_{b,ev} T}\right) - 1}$$

$$\frac{\cancel{eV}\cdot s \cdot Hz^3\, s^2\, \cancel{cm^2}}{\cancel{cm^2}\ \cancel{eV}} = Hz^3 s^3$$

$$\exp(x) = \frac{2 h_{ev} \nu_{ij}^3}{c^2 B_0} + 1$$

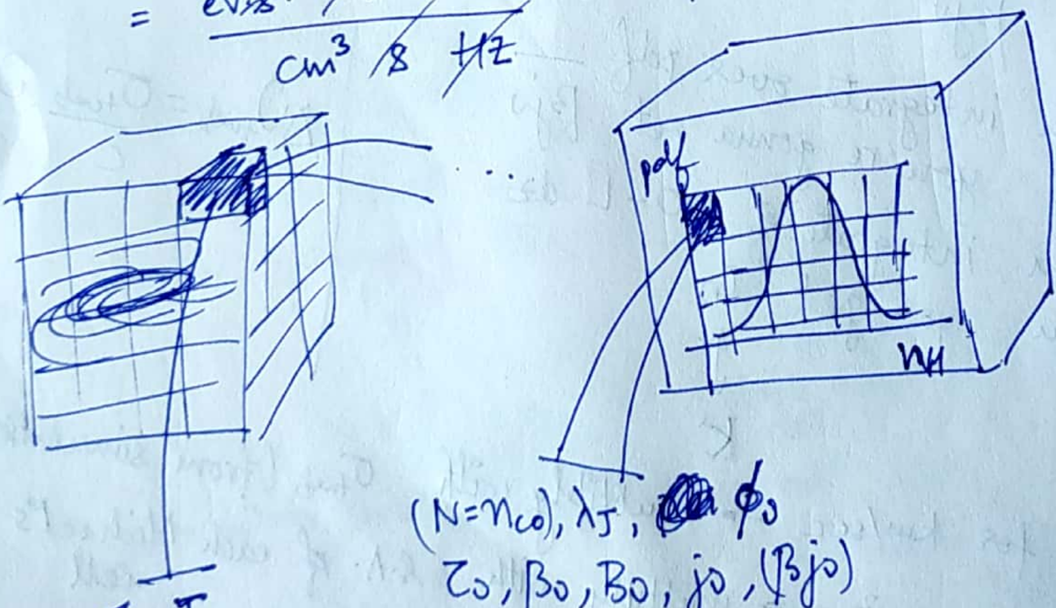
$$x = \log\left[\frac{2 h \nu_{ij}^3}{c^2 B_0} + 1\right] = \frac{h \nu_{ij}}{K_b T}$$

$$\therefore \boxed{T = \frac{h \nu_{ij}}{\log\left[\frac{2 h \nu_{ij}^3}{c^2 B_0} + 1\right] \cdot K_b}}$$

$$\frac{\cancel{eV}\cdot s\ Hz\ K}{\cancel{eV}} = Hz \cdot s \cdot K$$

$$j_0 = \frac{h_{ev} \nu_{ij} N n_i A_{ij} \phi_{ij}}{4\pi} = \frac{4.136\times10^{-15+11} \times 1.15 \times n_{co} \times 0.5 \times 7.2\times10^{-8-5} \times 4.792}{4\pi}$$

$$= \frac{eV\cdot\cancel{s}\cdot\cancel{Hz}}{cm^3\ \cancel{s}\ \cancel{Hz}} = eV/cm^3$$



I_0, T_0

$(N = n_{co}), \lambda_J, \phi_0$

$\tau_0, \beta_0, B_0, j_0, (\beta j_0)$

$i = 1 \quad j = 0$

$N = n_{co}$ [cm^{-3}]

$$\tau_\nu = \frac{h\nu}{4\pi} \lambda_J N (n_j B_{ji} - n_i B_{ij}) \times \frac{1}{\Delta\nu} = [\ ]$$

$$\Delta\nu = \frac{c_s}{c} \cdot \nu = [Hz] \quad ; \quad c_s = \sqrt{\frac{K_B \bar{T}}{m_H \cdot \mu}} \quad ; \quad \bar{T} = 10K, \ \mu_{co} = 28 = [cm\ s^{-1}]$$

$$\phi_\nu = 1/\Delta\nu = [Hz^{-1}]$$

$$\beta_\nu = \begin{cases} 1 - \frac{\tau_\nu}{2} \ ; & \tau_\nu < 0.01 \\ 1/\tau_\nu \ ; & \tau_\nu > 100 \\ \frac{1 - e^{-\tau}}{\tau_\nu} \ ; & \text{otherwise} \end{cases} = [\ ]$$

$$j_{ij} = \frac{h\nu}{4\pi} N\, n_i\, A_{ij}\, \phi_{ij} = eV\, cm^{-3} \cdot s^{-1}\, Hz^{-1}$$

$$j_\nu =$$

$$(\beta \cdot j_\nu) = \frac{h\nu}{4\pi} N\, n_i\, A_{ij}\, \phi_{ij} \cdot \beta_\nu = [eV\, cm^{-3}]$$

↳ what leaves the cell

$$I_\nu = \sum_{i=0}^{100} (\beta \cdot j_\nu)_i \cdot (pdf)_i \cdot ds$$

$= [eV\, cm^{-2}]$

$= [eV\, cm^{-2}\, s^{-1}\, Hz^{-1}]$

$$\sigma_s = \sqrt{\log(1 + (0.3M)^2)}$$

$$\bar{s} = -\sigma_s^2/2$$

$$s_{min} = -7\sigma_s + \bar{s}$$

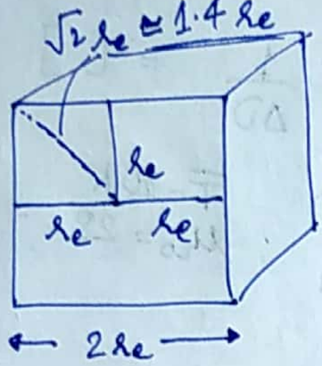
$$s_{max} = 7\sigma_s + \bar{s}$$

$$ds = \frac{s_{max} - s_{min}}{100} = [cm]$$

$$T_\nu = \frac{h\nu}{\log(f_{\nu\nu}) K_b} \quad ; \quad f_{\nu\nu} = \frac{2h\nu^3}{c^2 I_\nu} + 1$$

$= [K]$

4/6/2019



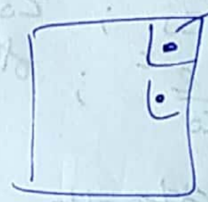
$$\text{edge} = 2r_e$$

$$SA = 6(\text{edge})^2 = 6(2r_e^2) = 24 r_e^2$$

given

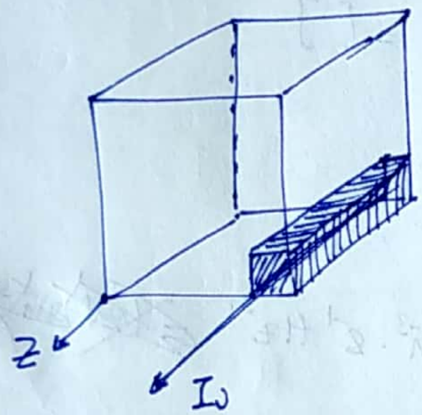
Total no. of cells = n

~~width of each cell = $\frac{n}{\text{edge}} = \frac{n}{2r_e}$~~

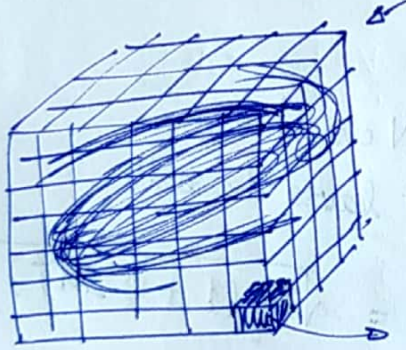


$I_\nu \; v_{los} \; l^2$

K km/s pc^2



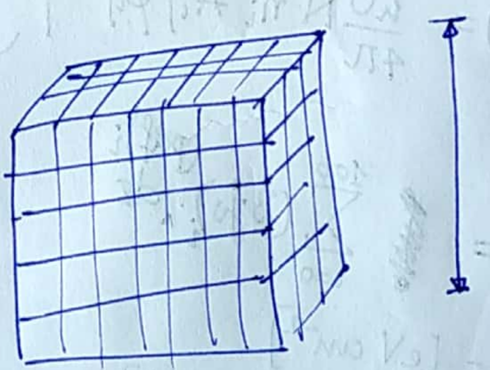
A whole simulation block (n cells)



one simulation cell

|||

sub-grid model



eV cm^{-2} Hz^{-1} s^{-1}

eV cm^{-3} Hz^{-1} s^{-1}

$$I_\nu = \int_0^L j_\nu \, dz$$

For one sim. cell

- $M, T, Z, G_0, \overline{n_H}, \overline{X}_{H2}, \overline{X}_{co}$
- j_ν
- $n_H[100]$, $n_{co}[100]$, $\lambda_J[100]$

$$v_{los} = \int_0^L v_z \, dz$$

18th July → Defence

5/6/2019

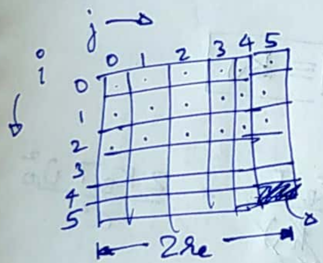
$$x = \frac{h_{eV}\nu}{K_b T}$$

$$B_\nu = \frac{2h_{eV}\nu^3}{c^2(\exp(x)-1)} = \frac{2h_{eV}\nu^3}{c^2(\cancel{1}+x-\cancel{1})} = \frac{2h_{eV}\nu^3}{c^2 \cdot x}$$

$$B_\nu = \frac{2\cancel{h_{eV}}\nu^{\cancel{3}\,2}}{c^2} \times \frac{K_B T}{\cancel{h_{eV}}\cancel{\nu}} = \frac{2\nu^2}{c^2}K_B T$$

$$\therefore T = \frac{c^2 B_\nu}{2\nu^2 K_B} = \frac{\cancel{cm^2}}{s^2} \times \frac{\cancel{eV}}{\cancel{cm^2}\cdot Hz \cdot s} \times \frac{1}{Hz^2} \times \frac{K}{\cancel{eV}}$$

$$= \frac{K}{s^3\,Hz^3}$$



$i = 0 \to len$, $j = 0 \to len$] → row-wise

$j = 0 \to len$, $i = 0 \to len$] → column-wise

→ I_ν

$$\hookrightarrow L_{co} = \frac{c^3}{2\nu_{10}^3} I_\nu$$

$dx = 2re/500$

$dy = 2re/500$

$$L_{co,Galaxy} = \iint L_{co}\,dx\,dy = \sum_{i=0}^{500}\sum_{j=0}^{500} L_{co}[i][j]\,dx\,dy$$

$$L_\odot = 3.828 \times 10^{28}\,W = 3.828 \times 10^{28}\,J/s = 2.38925 \times 10^{47}\,eV/s$$

5/6/2019

$i = 1,\ j = 0$

$$j_{10} = \frac{h\nu_{10}}{4\pi} N \overset{n_{co}}{n_1} A_{10}\, \phi_{10} \rightarrow \text{emissivity } [\mathrm{eV\ cm^{-3}\ s^{-1}\ Hz^{-1}}]$$

$$j_{10} = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \rightarrow \text{integrated emissivity} \quad [\mathrm{eV\ cm^{-3}\ s^{-1}}]$$

$$\bar{j}_{10} = \sum_{i=0}^{100} \beta\, j_{10}\, \mathrm{pdf}\, ds = \text{emissivity for each cell in the sim.} \quad [\mathrm{eV\ cm^{-3}\ s^{-1}}]$$

$$I_{10} = \int_0^L \bar{j}_{10}\, dz = \text{intensity of each pixel in the galaxy map} \quad [\mathrm{eV\ cm^{-2}\ s^{-1}}]$$

$$\bar{I}_\nu = \frac{I_{10}}{\nu_{10}} \quad [\mathrm{eV\ cm^{-2}\ s^{-1}\ Hz^{-1}}] \rightarrow \boxed{\equiv B_\nu}$$

$$\therefore \quad \bar{I}_\nu = \frac{2h\nu_{10}^3}{c^2 \cdot x} = \frac{2\cancel{h}\nu_{10}^{\cancel{3}\,2}}{c^2} \times \frac{K_B T}{\cancel{h\nu}} = \frac{2K_B T \nu_{10}^2}{c^2}$$

$$\therefore \quad T = \bar{I}_\nu \cdot \frac{c^2}{2\nu_{10}^2 K_B} \quad [\mathrm{K}]$$

$$\left\{ \frac{\cancel{eV}}{\cancel{cm^2}\, s\, Hz} \times \frac{\cancel{cm^2}}{s^2} \times \frac{1}{Hz^2} \times \frac{K}{\cancel{eV}} = \frac{K}{s^3\, Hz^3} = K \right\}$$

$$L_{co} = \bar{I}_\nu \cdot c = [\mathrm{K\ km/s}]$$

$$L_{co,galaxy} = L_{co} \cdot \underset{\text{width of map (pc)}}{L^2} = [\mathrm{K\ km/s\ pc^2}]$$

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METHOD-1 : Plotting_1-3 6/6/2019

$i=1, j=0$

$j_\nu = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \phi_\nu$ → emissivity [eV cm^{-3} s^{-1} Hz^{-1}]

$j_{10} = \frac{h\nu_{10}}{4\pi} N n_1 A_{10}$ → integrated emissivity → for each phase [eV cm^{-3} s^{-1}]

$\bar{j}_{10} = \sum_{i=0}^{100} \beta j_{10}\, \mathrm{pdf}\, ds$ → emissivity for each cell in the sim [eV cm^{-3} s^{-1}]

$I_{10} = \int_0^L \bar{j}_{10}\, dz$ = intensity of each pixel in the galaxy map [eV cm^{-2} s^{-1}]

$I_\nu = \frac{I_{10}}{\Delta\nu}$, $\Delta\nu = \nu_{10} \frac{\Delta v}{c}$, $\Delta v = 100$ km/s $= 10^7$ cm/s

$$\boxed{T_\nu = \frac{c^2}{2\nu_{10}^2 K_B} I_\nu} \quad [K]$$

$$= \frac{c^2}{2\nu_{10}^2 K_B} \frac{I_{10}}{\Delta\nu} = \frac{c^2}{2\nu_{10}^2 K_B} \frac{I_{10}}{\nu_{10}\Delta v} \cdot c = \underbrace{T_\nu'}_{K} \cdot \underbrace{\frac{c}{\Delta v}}_{[\,]}$$

$$(T_\nu \cdot \Delta v) = \underbrace{\frac{c^2}{2\nu_{10}^2 K_B} \frac{I_{10}}{\nu_{10}}}_{K} \cdot \underbrace{c}_{km/s} = L_{co}$$

↳ Luminosity of each pixel in the map

$L_{co,\,galaxy} = L_{co} \cdot (\mathrm{edge})^2$ → Total Luminosity of the galaxy [K km/s pc^2]

METHOD - 2 : (1.5)

$i=1,\ j=0$

$j_\nu = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \phi_\nu$ → emissivity $[\mathrm{eV\ cm^{-3}\ s^{-1}\ Hz^{-1}}]$

$j_{10} = \frac{h\nu_{10}}{4\pi} N n_1 A_{10}$ → integrated emissivity for each phase $[\mathrm{eV\ cm^{-3}\ s^{-1}}]$

$\bar{j}_{10} = \sum_{i=0}^{100} j_{10} \cdot \beta \cdot \mathrm{pdf}\ ds$ → emissivity of each cell in the sim. $[\mathrm{eV\ cm^{-3}\ s^{-1}}]$

dv = Volume fraction = $\mathrm{pdf} \cdot ds$

$dV = dv \cdot (\Delta x)^3$ ← cell-width of each sim. cell. in $[\mathrm{cm}]^3$

$\therefore\ l_{CO}$ = Luminosity of each cell = $\bar{j}_{10} \beta \cdot dV$

$= j_{10} \beta\, dv\, (\Delta x)^3 = j_{10} \beta\, \mathrm{pdf}\ ds\ (\Delta x)^3$

$\therefore\ \boxed{l_{CO} = \bar{j}_{10} \cdot (\Delta x)^3}$ $[\mathrm{eV\ s^{-1}}]$

$L_{CO,\ galaxy}$ = Luminosity of the galaxy = $\sum_{i=0}^{\mathrm{len}(M)} l_{CO}$ $[\mathrm{eV\ s^{-1}}]$

$L_{CO} = l_{CO} / L_\odot$

→ l_{CO} vs $\log(\bar{n}_H)$

→ $L_{CO} = ? / L_\odot$

→ $\bar{j}_{10}$ vs $\log(\bar{n}_H)$

✓ L_{CO} vs $\log(\bar{n}_H)$

✓ $\log(L_{CO})$ vs $\log(\bar{n}_H)$

~~→ $\bar{j}_{10}$ vs $\log(\bar{n}_H)$~~

→ $\log(\bar{j}_{10})$ vs $\log(\bar{n}_H)$

~~→ $L_{CO,\ galaxy} \approx 10^x L_\odot$~~

Also : (1.6)

Need to plot the phase - luminosity of ~~each~~ the sub-grid model.

$\lambda_J = \lambda_J[\ ]$

$N = n_{co}[\ ]$

$\Delta x =$

$i=1,\ j=0$

$$j_0 = \frac{h\nu_{10}}{4\pi} N\, n_1 A_{10} \phi_0$$

$$j_{10} = \frac{h\nu_{10}}{4\pi} N\, n_1 A_{10} \qquad [eV\ cm^{-3}\ s^{-1}]$$

$$\ell_{co} = j_{10} (\Delta x)^3 \qquad [eV\ s^{-1}]$$

$$L_{co} = \ell_{co} / L_\odot$$

→ ℓ_{co} vs $\log(n_H)$

→ j_{10} vs $\log(n_H)$

→ L_{co} vs $\log(n_H)$

→ $\log(L_{co})$ vs $\log(n_H)$

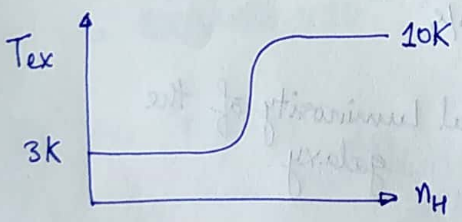
~~$j_{10}\beta\, pdf$ vs $\log(n_H)$~~

→ Graph from the paper.

→ $\log(j_{10}\beta\, pdf)$ vs $\log(n_H)$

Also :

Non-LTE to regulate n_i → n_i will ↓

→ 

METHOD-1 : plotting-1.4

$i=1,\ j=0$

$j_\nu = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \phi_\nu$ → emissivity $[\mathrm{eV\ cm^{-3}\ s^{-1}\ Hz^{-1}}]$

$j_{10} = \frac{h\nu_{10}}{4\pi} N n_1 A_{10}$ → integrated emissivity $[\mathrm{eV\ cm^{-3}\ s^{-1}}]$

$\bar{j}_{10} = \sum_{i=0}^{100} j_{10} \cdot \beta \cdot pdf \cdot ds$ → emissivity for each cell in the sim. $[\mathrm{eV\ cm^{-3}\ s^{-1}}]$

$I_{10} = \int_0^L \bar{j}_\nu\, dz$ → Intensity of each pixel in the Galaxy map $[\mathrm{eV\ cm^{-2}\ s^{-1}}]$

$I_\nu = \frac{I_{10}}{\Delta\nu}$ $[\mathrm{eV\ cm^{-2}\ s^{-1}\ Hz^{-1}}]$; $\Delta\nu = \nu_{10}\frac{\Delta v}{c}$; $\Delta v = 100\ \mathrm{km/s} = 10^7\ \mathrm{cm/s}$

$$\left\{ T = \underbrace{\frac{c^2}{2\nu_{10}^2 K_B} I_\nu}_{[K]} \right\} = \frac{c^2}{2\nu_{10}^2 K_B} \frac{I_{10}}{\nu_{10}\Delta v} \cdot c$$

$$\therefore (T\cdot\Delta v) = \underbrace{\left(\frac{c^2}{2\nu_{10}^2 K_B}\frac{I_{10}}{\nu_{10}}\right)}_{K} \cdot \underbrace{c}_{km/s}$$

$$L_{co} = \underbrace{(T\cdot\Delta v)}_{K\ km/s} \cdot \underbrace{(edge)^2}_{pc^2}$$ → Total Luminosity of the galaxy

Results:

$T \sim$ (mean value) 10^{-4} K

$L_{co} = 8.34 \times 10^{11}\ \mathrm{K\ km\ s^{-1}\ pc^2}$

If I use, $L_{co} = (I_{10}\cdot c)\cdot(edge)^2$

Then $L_{co} = 2.127 \times 10^{9}\ \mathrm{K\ km\ s^{-1}\ pc^2}$

METHOD - 2 : (1.7) - using 1.4 results

$i=1, j=0$

$j_\nu = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \phi_\nu$ → emissivity [eV cm^{-3} s^{-1} Hz^{-1}]

$j_{10} = \frac{h\nu_{10}}{4\pi} N n_1 A_{10}$ → integrated emissivity [eV cm^{-3} s^{-1}]

$\bar{j}_{10} = \sum_{i=0}^{100} j_{10} \beta \, pdf \, ds$ → emissivity for each cell in the sim. [eV cm^{-3} s^{-1}]

dx = width of each cell in the sim → [cm]

$l_{co} = \bar{j}_{10} \cdot (dx)^3$ → Luminosity of each cell in the sim. [eV s^{-1}]

$L_{co} = \sum_{i=0}^{\text{all cells}} (l_{co})_i$ → Luminosity of the Galaxy [eV s^{-1}]

Result :

$L_{co} = 10^{1.43} L_\odot$

$= 6.487 \times 10^{46}$ eV s^{-1}

$L_\odot = 2.4342 \times 10^{45}$ eV s^{-1}

In the paper,

$L_{co} = 10^{4.85} L_\odot$

$\mu = 30$

Kinetic Temp., $T_K = 45$ K

SFR = 100 $M_\odot$/yr

$M_* = 10^{10} M_\odot$

$z=6$

→ L_{co} vs $\log(\bar{n}_H)$

→ $\bar{j}_{10}$ vs $\log(\bar{n}_H)$

]- attached

Sub-grid :

$i=1,\ j=0$

$$j_0 = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \phi_\nu \rightarrow [\mathrm{eV\,cm^{-3}\,s^{-1}\,Hz^{-1}}]$$

$$j_{10} = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \rightarrow [\mathrm{eV\,cm^{-3}\,s^{-1}}]$$

$$l_{co} = j_{10} \cdot \beta \cdot pdf \cdot (dx)^3 \rightarrow [\mathrm{eV\,s^{-1}}]$$

where, dx = mean-width of a cell in the sim.

$= 3.5 \times 10^{20}$ cm

$$L_{CO} = l_{co}/L_\odot$$

Result :

1. L_{CO} vs $\log(n_H)$ – attached
2. $(j_{10} \cdot \beta \cdot pdf)$ vs $\log(n_H)$ – attached.

$$j_{10} = \frac{h\nu_{10}}{4\pi} N n_1 A_{10} \Rightarrow \mathrm{eV\,cm^{-3}\,s^{-1}\,sr^{-1}}$$

New $\therefore\ j_{10} = h\nu_{10} N n_1 A_{10} \Rightarrow [\mathrm{eV\,cm^{-3}\,s^{-1}}]$

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(1)

$R_{Total} = 6.5 \times 10^6$
$R_{core} = 4.55 \times 10^6$
$M_{atmos} = 7.1794 \times 10^{19}$

$R_{Total}^5 - R_{core}^5$
$num = 9.6528 \times 10^{33}$

$R_{Total}^3 - R_{core}^3$
$den = 1.8043 \times 10^{20}$

$I_{atmos} = \frac{2}{5} M_{atmos} \frac{num}{den} = 1.5357 \times 10^{33}$

$I_{core} = 3.4308 \times 10^{37}$

$I_T = 3.4310 \times 10^{37}\ kg\ m^2$

~~1~~ ~~2~~ 3 4 5 ~~6~~ ~~7~~ ~~8~~
~~9~~ ~~10~~ ~~11~~ ~~12~~ ~~13~~ 14 15 ~~16~~
~~17~~ 18 19 20 21 22

(2) $R_{core} = 9.75 \times 10^5$
$M_{atmos} = 1.0891 \times 10^{20}$

$den = 2.7370 \times 10^{20}$
$num = 1.1602 \times 10^{34}$

$I_{atmos} = 2.54 ~~~~ 99 \times 10$

$I_{core} = 1.5491 \times 10^{34}$

$I_T = 1.5746 \times 10^{34}$

4: Simulation Course in ETH : Yes
5: High-Perf. Comput. in ETH : Yes
14: Alogorithm Lab in ETH : Yes
15: Neural Network theory in ETH : Yes (pure maths)
18: Computational Astrophysics in UZH (Lucio) : Yes